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Diamond-Based High Performance Materials

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Diamond-Based High Performance Materials

926C0043A Tokyo MUKI SHINSOZAI SANGYO TAISAKU CHOSA ITAKU CHOSA KENKYU HOKOKUSHO in Japanese Mar 91 pp 1-151

[Report by the Japan Fine Ceramics Association under MITI Contract: "Inorganic Materials (New Diamond) Industrial Policy Investigation"]

[Excerpts] [Passage omitted]

2.2. Applications of Optical Properties

2.2.1. X-Ray Applied Parts

(1) X-Ray Transmitting Window

As can be seen in Figure 2.7, the coefficient of X-ray absorption increases in a simple way with an increase in wavelength, except for an abnormality at the absorption edge. Generally speaking, this coefficient is lower in cases of lighter elements and lower densities. Therefore, the materials that are suitable for windows are limited to H, B, N, C, Si, Be, organic materials, and so forth. Other materials are unsuitable because of their high degrees of absorption. As shown in the illustration, the absorption coefficient of diamond is generally low, and the absorption edge is seen at a wavelength close to 40 Angstroms. Therefore, in a range from 40-700 Angstroms it exhibits the lowest absorption coefficient among all materials. The performance required of a window material is common with the properties required of an X-ray mask substrate material, which will be described in the next paragraph.

The materials commonly used for X-ray windows include Be (beryllium) thin plates and parylene film. Windows for X-ray bulbs and detectors need to be manufactured with materials having the highest possible X-ray transmission coefficient. These windows are used for such purposes as taking out high-strength X-rays from an X-ray source for X-ray lithography, as shown in Figure 2.8. The size of windows for these purposes must be about 10 cm^2.

There is, for example, an X-ray transmission window fitted with a diamond film approximately 0.5 μm thick that has been fabricated on a silicon substrate by microwave CVD. The window also is fitted with a metallic grid for reinforcement. This window has been trial-manufactured as a solid X-ray detector window with a diameter of 20 mm. It needs to be tolerant of a difference in pressure of 1 atm, but its strength is not as yet sufficient. The characteristic X-ray wavelength of such lightweight elements as carbon, boron, and oxygen is in a 30-100 Angstroms range, and in this vicinity the absorption of Be metal, which has been used to date, is very remarkable. Therefore, there is a great advantage in using diamond.

(2) X-Ray Mask

There are expectations that X-ray exposure will prove to be viable as a pattern transcribing method involving little bleeding and producing superior resolving power. These expectations are based on such strong points as a minimal drop in contrast due to diffraction, a short range of secondary electron flight from resist or a substrate, a high coefficient of transmission to resistor dust, a high step coverage due to monolayer resist, and a low rate of failure.

At the same time, however, X-ray exposure is incapable of effecting mask-reduced pattern-projected exposure through the use of optical lenses, as in the case of ultraviolet exposure. At the submicron level, therefore, an X-ray absorption pattern with an aspect ratio of 1 or more must be formed. To realize a practical mask contrast, a mask pattern must be formed with a heavy metal film having a size of not less than 1 μm. In spite of such problems, it is believed that X-ray exposure will prove to be an indispensable technique for manufacturing LSI's at the level of 64 Mbit or higher.

An X-ray mask consists of an X-ray transmissible support film with an X-ray absorption pattern formed on it, and a frame to support the entire mask, as shown in Figure 2.9.

Because diamond has a high X-ray transmission coefficient, as shown in Figure 2.7, it is superior in performance as an X-ray transmissible support film. Various efforts aimed at utilizing this phenomenon are underway. For a metal film for pattern formation, to date a thickness of 1 μm or more has had to be taken by using a substrate showing a high X-ray transmission coefficient. However, using a diamond substrate makes it possible to reduce the film thickness by more than half, and this facilitates mask formation greatly. In synthesizing a diamond thin film by CVD, silicon can be used for the substrate, but silicon is also advantageous because it can be easily processed as a support frame through etching. The conditions required of X-ray mask substrates are summed up as follows:

(a) Transparency in X-rays: Intensity of transmitted X-rays, high aspect ratio

(b) Flatness: Pattern processing accuracy

(c) Smoothness: Pattern distortion, out of focus

(d) Uniformity of film thickness: Uniformity of exposure strength

(e) Low coefficient of thermal expansion: Mask deformation due to a rise in temperature during X-ray irradiation

(f) Mechanical strength: Ease of treatment during handling

(g) Water resistance, resistance to chemicals: Etching resistance during pattern formation

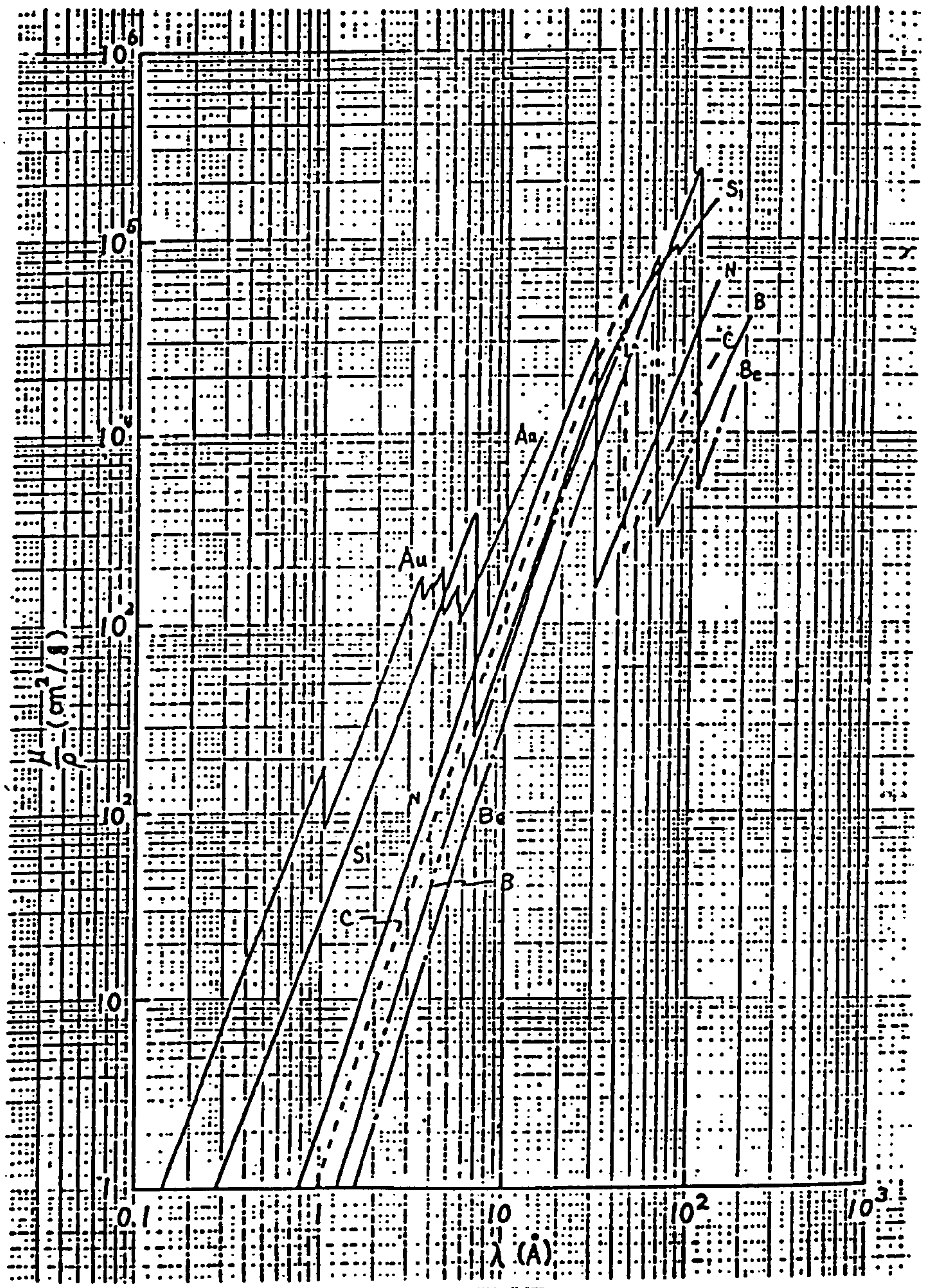

Figure 2.7. Relationship Between Wavelength and X-Ray Absorption Coefficient

(h) Resistance to X-ray irradiation damage: Mask deformation

(i) Visible ray transparency: Accuracy of mask positioning by visible rays

The principal mask substrates reported to date are summarized in Table 2.6. They include $P^{++}Si$, Al_2O_3, $Si_3N_4/SiO_2/Si_3N_4$ composite film, SiC, SiN_x, BN/polyimide composite film, BHN, Ti, mylar, and Si_3N_4/parylene-N composite film. the characteristics of those producing comparatively promising results are summed up as follows:

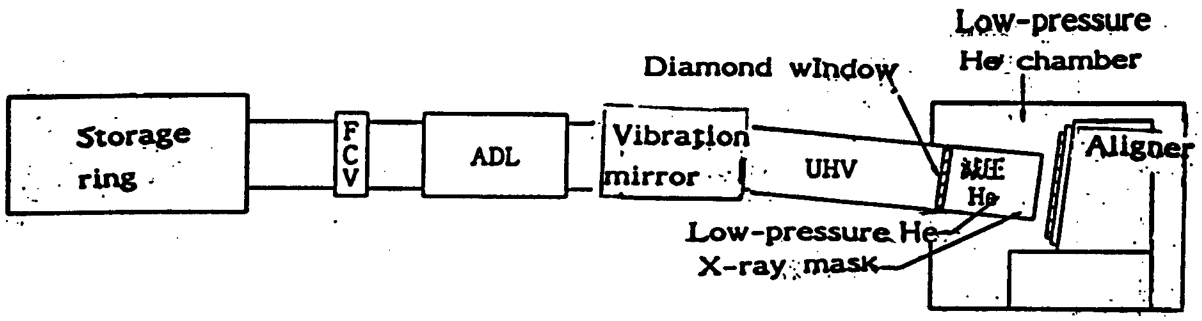

Figure 2.8. Transmission Window for Luminous Source X-Ray Lithography

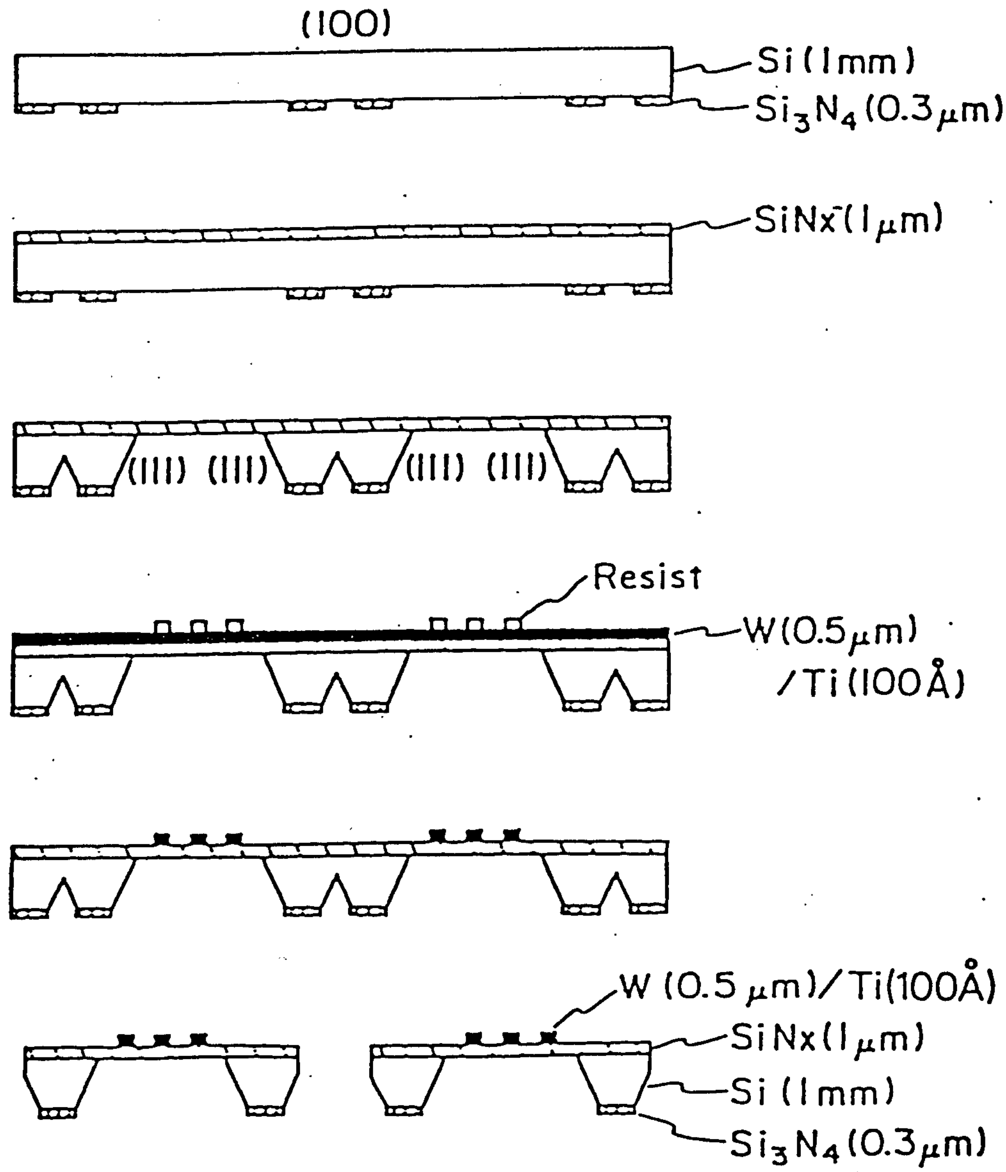

Figure 2.9. Configuration of an X-Ray Mask

BN/polyimide substrate: The coefficient of soft X-ray transmission is high, and a Pyrex glass support frame is fixed.

SiNx substrate: The thickness is 1 μm-2 μm, and the stress in the film is reduced by 1 - 2 x 10^8 dyn/cm^2.

$P^{++}Si$ substrate: This is a high-density B-doped Si substrate, with the stress reduced by Ga^+ ion implantation.

Table 2.6. Comparison of Performance Among Various X-Ray Exposure Masks

X-ray mask substrate	Developer Fiscal year	Evaluation items: Smoothness	Flatness	Size stability	Coefficient of thermal expansion	Mechanical strength	Tolerance for chemicals	Coefficient of visible ray transmission	Productivity	X-ray attenuation factor (dB/μm): Mo L 5.4A	Si K 7.1A	Al K 8.3A	Cu L 13.3A	C K 44A	Remarks
P^{++}	1973 MIT	o	x	o	o	Δ	o	x	Δ	2.0	0.3	0.45	2.0	11	In a φ2" mask there is a warp measuring several μm.
MYLAR	1974 BTL	x	Δ	x	x	Δ	x	o	o	0.1	0.4	0.5	2.3	2.2	There are many microscopic projections, which are to be fixed in a frame by using an adhesive.
KAPTON	1975 GM	x	Δ	x	x	Δ	x	o	o	0.1	0.3	0.5	2.0		Same as above
Al_2O_3	1975 Fujitsu	o		o	x	Δ	o	o	o	1.8	4.5	1.5	7.7	400	The biggest defect is that the coefficient of thermal expansion is high. The degree of X-ray absorption also is high.

Table 2.6. Comparison of Performance Among Various X-Ray Exposure Masks (Continued)

SiO_2/Si_3N_4	1976 IBM	o	Δ	o	o	x	o	o	o	1.4	0.5	0.8	3.0	11	The mechanical strength is low, and it can hardly be used through sharpening.
$Si_3N_4/SiO_2/Si_3N_4$	1976 NEC	o	Δ	o	o	Δ	o	o	Δ	1.2	0.5	0.8	3.0	11	The weakness is that the productivity is low.
PARYLENE/Si_3N_4	1977 Oki Electric	o		o	o	Δ	x	o	o	0.3	0.4	0.6	2.2	8.1	Parylene is formed by a low-pressure CVD method.
POLYIMIDE	1977 MIT	o	Δ	Δ	x	Δ	x	o	o	0.1	0.3	0.5	2.0		Glass, Si, and so forth are used for the frame. The composition is the same as that of kapton.
SiC	1978 TI	Δ	Δ	o	o	Δ	o	Δ	o	2.0	0.5	0.8	3.6	150	The CVD method is effective.
P.I./BN	1979 BTL	Δ	o	o	o	o	x	Δ	Δ	0.2	0.4	0.6	2.1		The flatness is to be improved by sticking it to a Pyrex ring.

Table 2.6. Comparison of Performance Among Various X-Ray Exposure Masks (Continued)

SiN (LP-CVD)	1980 NTT	Δ	Δ	o	o	Δ	o	o	o	1.6	0.5	0.8	3.0	11	The stress is to be reduced through enriching it by Si. It tends to give rise to Si particles.
SiN (PCVD)	1980 NEC	o	Δ	o	o	Δ	o	o	o	1.6	0.5	0.8	3.0	11	The stress is to be reduced through enriching it with Si.
Ti	1980 PE	o				o	o	x		1.6	3.1	4.4			It absorbs a great deal of X-rays, and is not transparent to visible rays.

Next, we will describe an X-ray absorption mask pattern to be formed on an X-ray transmissible support film. When the linear absorption coefficient and the film thickness of an X-ray absorption pattern material are represented by μ and t respectively, the contrast of the X-ray mask is expressed in terms of $C = \exp(-\mu t)$. Such heavy metals as Au, Ta, and W, which have a high linear absorption coefficient and good processibility, are used for X-ray absorption patterns. For pattern drawing, the resist undergoes superfine processing by such methods as electron beam exposure or an FIB technique, and, using the resist pattern as a mask, a metal film is formed by such physicochemical methods as electric plating, reactive ion etching (RIE), and ion milling. Withstanding such processing is also a quality necessary for mask substrates.

When diamond is used for mask substrates, the absorption coefficient is low, within the 40-100 Angstroms wavelength range, and the thermal conductivity is high, making it possible to restrain a rise in the temperature of the mask substrates during X-ray irradiation. Because the coefficient of thermal expansion also is low, it can be expected that the degree of deformation of the mask due to thermal expansion will be small. The mechanical strength of diamond is known to be great. There have been reports on a polycrystalline film fabricated on a 4-inch silicon substrate by the microwave CVD method. These reports have described the conditions for synthesis, the quality of the film obtained, its transmission coefficient, stress, thermal expansion coefficient, thermal conductivity, and so forth. Depending on the conditions for synthesis, the ratio between the diamond and graphite components in the film, and the amount of hydrogen in the film, will vary, and the surface smoothness, the stress in the film, and so forth are different. However, in all cases the properties necessary for mask substrates display values close to those of high-pressure synthesized monocrystalline diamond.

2.2.2. Infrared Parts

Optical properties include transmission, reflection, absorption, luminescence, and refraction factors. The main properties currently used in infrared parts are transmission and reflection. Diamond is optically isotropic, and is highly transparent to wavelengths ranging from ultraviolet to far infrared, but it absorbs them in various wavelengths because of the mixture of impurities. Pure diamond of the II a type will absorb these wavelengths to a lesser degree, and is most suitable when used as an optical material. The ultraviolet absorption edge of type II a diamond measures about 230 nm, and visible rays are transmitted across the entire wavelength range. Diamond of this type is transparent except in the

case of absorption peculiar to diamond in a 2.5-6 μm wavelength range for both infrared and far infrared radiation.

Up to this point, the optical application of diamond has been limited to fairly specific uses, such as a material for the window of an infrared detector for a Venus probe, the window of an X-ray detector for analytic purposes, and so forth. However, if diamond that is highly transparent and fairly large in size becomes freely obtainable, it conceivably would fill quite a number of needs as an optical material for wavelengths ranging from ultraviolet to infrared.

There are generally three wavelength bands used as infrared rays—1 μm, 3-5 μm, and 8-13 μm bands. In the 1 μm band, glass materials in common use are serviceable, and diamond is absorbent in the 3-5 μm band. Therefore, the use of infrared rays focuses on the 8-13 μm band. There are only four optical materials that are serviceable in this band—Ge, ZnSe, ZnS, and chalcogenide glass. However, the mechanical strength, environmental resistance, and other characteristics of these materials are not sufficient, either. If diamond can be used, the degree of freedom in optical designs will expand. Because it takes in visible rays as well, diamond has the advantage of facilitating optical adjustment. When it is to be used for an infrared image photography system or the like, it is necessary to ensure that the diameter of the optical window is consistent with the sensitivity of an infrared detecting device.

It is conceivable that diamond thin film can be used to protect optical materials from infrared rays. Such a deliquescent material as alkali halide becomes usable in a bad environment by coating it with diamond. When it is used as a thin film, the absorption that is peculiar to diamond in approximately the 5 μm band is so slight that it is fully usable in the 3-5 μm band as well.

Diamond is highly refractive, and provides 15 percent surface reflection per plane. To elicit the optical performance of diamond, therefore, a film to prevent reflection is absolutely necessary. In this case, a film of low durability would completely negate the advantage of diamond. Therefore, sufficient durability is required of the reflection preventing film as well.

Hard carbon thin film (i carbon) can be produced by a number of methods, such as ion beam or plasma CVD. As for its optical properties, the optical band gap is in a 0.8-3.0 eV range, and the index of refraction is about 1.8-2.3. It is given a yellow or brown color because it is absorptive in the visible range, but it is comparatively transparent to infrared rays. The hardness and refraction factor of the i carbon are much lower than those of diamond, and the absorption in the infrared band is also remarkable (four-fold at a wavelength of 5 μm and 4,000-fold at 10 μm). Compared to diamond thin film, it is capable of coating even at low temperatures, and it forms a smooth, continuous film even when it is thinly applied. Therefore, the possibility of its being used as an optical thin film is rather greater than that of diamond film. The i carbon is highly transmissible in the infrared band, and therefore it is often used in this band. Because its index of refraction is most suitable for an infrared reflection preventing film based on Si or Ge, this carbon is used as a film to prevent the reflection of highly refractive infrared rays. It is also used as a protective film for infrared reflecting mirrors.

2.2.3. Laser Parts

With the increase in the output of CO_2 gas lasers, and the development of free electron lasers, optical materials (window and mirror materials) with high levels of heat resistance are being sought. Currently, ZnSe is the material most frequently used, but it can be said that diamond is an ideal optical material because it is far superior to other materials in terms of heat resistance and heat conductivity. It also is transparent, all the way from the infrared to the ultraviolet wavelength band. With regard to the heat distortion of diamond due to laser beams, experimental and theoretical studies are underway. But from the thermal point of view, diamond is regarded as capable of withstanding laser energy 1,000 times as high as ordinary glass at room temperature, and 25,000 times at 80K. In addition, diamond can transmit energy amounting to several hundred MW.

Material breakdown (optical breakdown) occurs when the electric field caused by light is strong, as in the case of a free electron laser. The threshold value of diamond is 6-10 J/cm^2, which is much higher than those of other materials.

Figure 2.10 is a conceptional diagram of a window for a high-output laser. The diamond is 1 cm across, and its periphery is cooled with liquid nitrogen. A matching material is inserted to raise the efficiency of heat conduction from the diamond to a low-temperature holder. It is predicted that using this formula will make it possible to transmit laser energy of about 400 MW.

In the ultraviolet wavelength band, which ranges up to about 220 nm, there are only two kinds of optical materials used for experimental purposes—fluorite and quartz. Diamond is a promising optical material for use in this wavelength band range. It probably is possible to

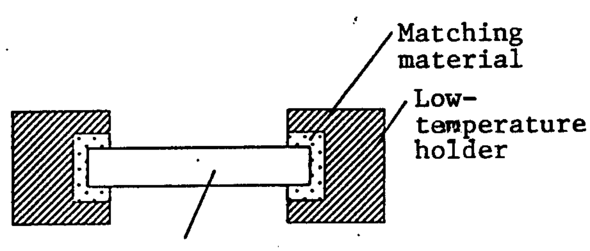

Figure 2.10. Window for High-Output Laser

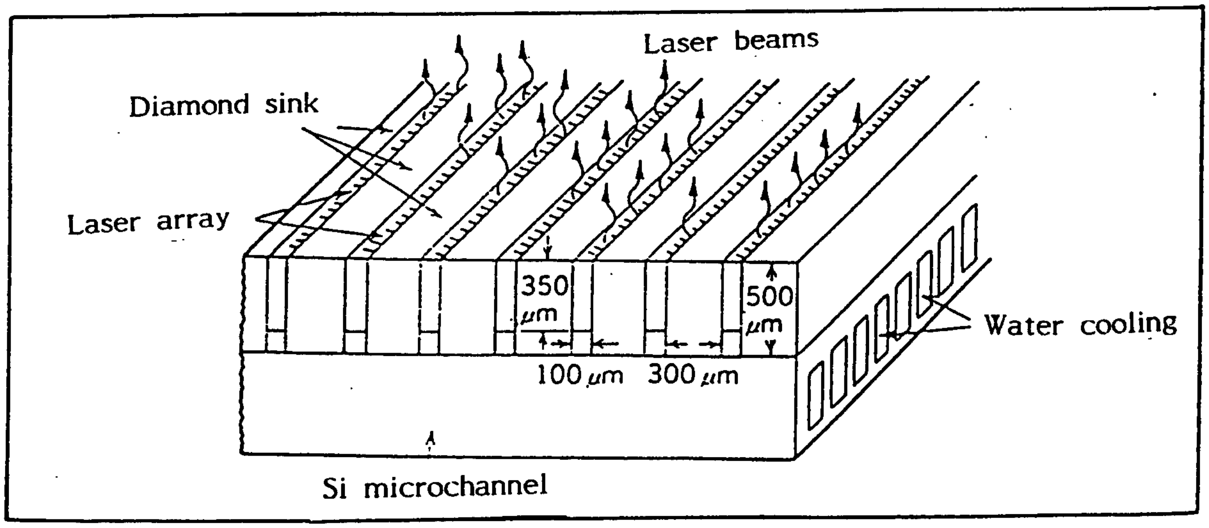

Figure 2.11. Two-Dimensional Large-Output Semiconductor Laser Using Diamond Heat Sinks

use diamond as an optical material for ultraviolet lasers, and for excimer lasers in particular.

2.3. Application of Thermal Properties

2.3.1. Heat Sink

In the case of semiconductor devices, degradation of performance and life span due to heat generation at the time of operation is a big problem. For this reason, there are many contrivances for heat radiation structures around devices. One of these is a method to give a higher degree of thermal conductivity close to the operational part of a device and to cool it through its contact with a substance having a large thermal capacity. A metal having a high level of thermal conductivity, such as copper, is ordinarily used. However, in the case of such devices as semiconductor lasers for optical communications that involve a high degree of local heat generation because of a high density of power consumption in the active region, monocrystalline diamond having a thermal conductivity about five times as high as copper near room temperature is used as a heat sink material in order to reduce heat resistance as far as possible. Such a diamond heat sink can be as small as 1 mm^2 and about 0.3 mm thick. If a film with a thermal conductivity close to that of a single crystal can be manufactured at low cost (on the same level as BeO, for example) and given the progress in gas phase synthesis technology, it might be used in large amounts.

At the same time, semiconductor lasers are beginning to be used, through an increased output or integration, for solid laser excitation, for example, as a light source with a high degree of coherency. Figure 2.11, for example, shows a two-dimensional laser array aimed at an optical output in the kW class for use as a light source for a highly efficient solid laser system that hopefully can be used for such purposes as uranium enrichment as well. It is conceivable that monocrystalline diamond about 1 cm long can be used as a heat sink. Isotope-free, large-size single crystals with higher heat conductivity, as described in paragraph 1.5, are thought to be suitable for such applications.

2.3.2. IC Substrate

In addition to such discrete devices as laser elements and high-output microwave transistors where diamond can be used as heat sinks by taking advantage of the fact that it has the highest thermal conductivity among materials, diamond produced by a gas phase method might be used as heat sinks for multichip packages and three-dimensional IC's, because it has the advantage of being obtainable with a large area, and in a film state it can be utilized positively.

Figure 2.12 shows the thermal conductivity of materials with the structure of diamond. It is well known that diamond has the highest thermal conductivity of all materials, exceeding 2,000 W/mK. After all, cBN and diamond are the only materials that are insulating, and, moreover, show high degrees of thermal conductivity exceeding 500 W/mK. As is well known, up to now it has not been possible to synthesize either material, except by a superhigh pressure synthesis technology. Therefore, they have been extremely expensive, and, moreover, unobtainable except in a size of about 10 mm^2 at most. Therefore, the sphere in which they are usable has been limited. If large-area substrates become obtainable at low price by using a gas phase method, they conceivably will be used in a number of ways.

For high-density wiring board multichip packages, multilayer wiring boards consisting primarily of alumina or

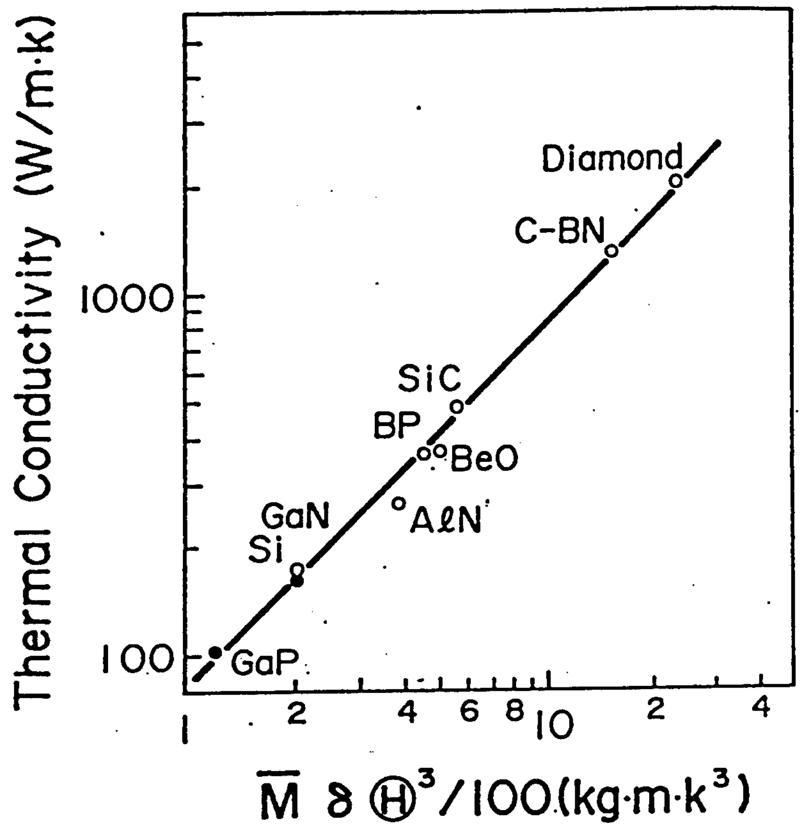

Figure 2.12. Thermal Conductivity of Materials of Diamond Structure

SiO_2 have been put to practical use, as shown in Figure 2.13. These multilayer wiring boards, loaded with several LSI chips each, are used as the arithmetic circuit substrates for computers. With increased speed and output, the technology for the efficient radiation of heat generated from LSI chips will become more and more important in the future. As is well known, substrate materials showing high levels of thermal conductivity include BeO, SiC, AlN, BN, and diamond. Applications of AlN to multichip packages are progressing. Diamond is potentially superior to AlN in thermal conductivity, dielectric constant, mechanical strength, and so forth, and therefore it might be used for multilayer wiring boards.

There is as yet no instance of exploring the application of diamond to three-dimensional IC's, but a method to ease local heating due to increased device integration is conceivable. As shown in Figure 2.14, it can be expected that the degree of integration and speed will increase if a rise in device temperature is restrained by inserting an insulating layer for thermal expansion between device layers. The heat generating part of a device is concentrated in an extremely narrow region of the pn junction, and therefore it is anticipated that a rise in temperature can be eased through effective thermal diffusion and dissipation.

When directly coating a device layer with diamond film as an insulating layer for thermal diffusion, no damage should be inflicted on the lower device layer. However, the problem with current technologies is that the temperature for film fabrication is too high. What can be thought as the second best measure is to use an adhesive method for the diamond film. For this method of adhesion, the quality of the adhesive, the method of applying it, the technique for connecting the lower and upper device layers, and so forth leave room for study. But this method has an advantage in that the restrictions on the film fabrication temperature are lifted. [passage omitted]

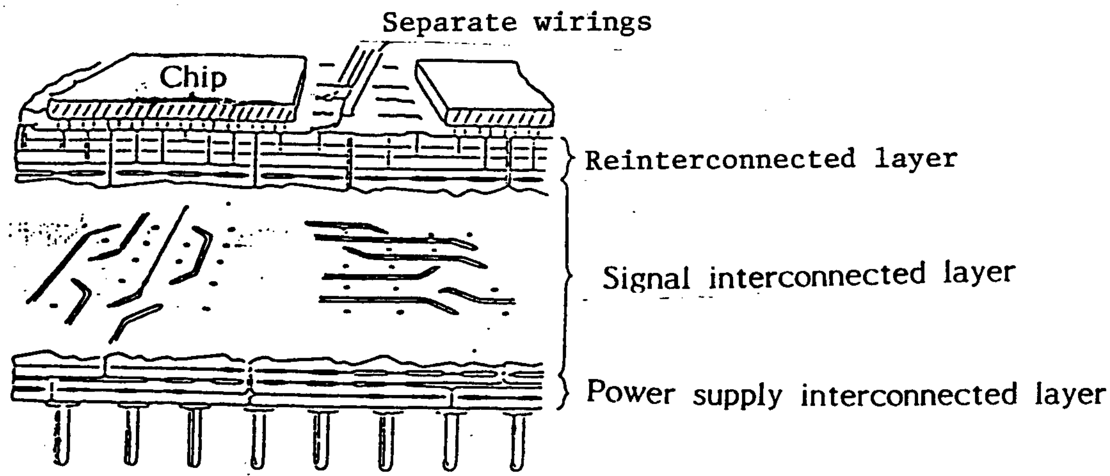

Figure 2.13. Multilayer Wiring Board

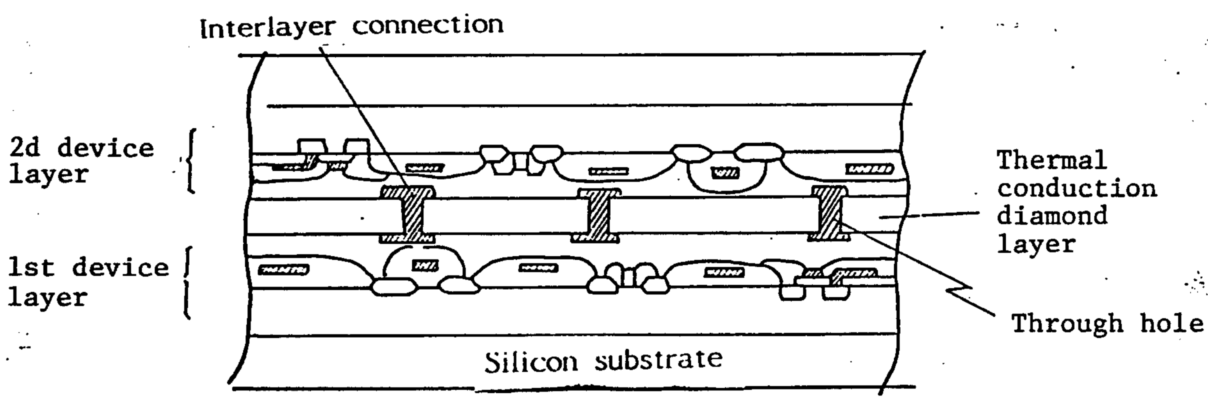

Figure 2.14. Possibility of Diamond Application to Laminate Devices

2.5. Applications of Mechanical Properties

2.5.1. Coated Cutting Tools

Diamond-coated cutting tools are expected to replace the tools that currently use sintered diamond bits.

The big problem with diamond-coated cutting tools lies in the strength of the adhesion between the base substance and the diamond. Diamond does not attain epitaxial growth on a different kind of base substance. Its growth develops after nucleation on the surface, and then it is turned into a film. To increase the adhesive strength, therefore, it is necessary to increase the density of nucleation, or to use a base substance whose thermal expansion is similar to that of diamond, or to use a base substance that displays epitaxial growth.

In the case of cutting an aluminum alloy with a diamond-coated cutting tool using Si_3N_4 as a base body, the diamond film does not flake off when the silicon content is 12 percent, and the tool exhibits a stable cutting performance. However, the film flakes off when the silicon content reaches 24 percent.

Thus, a diamond-coated cutting tool using a base body that is different from diamond has a problem in that the film flakes off, and thus it can hardly be used for materials that are difficult to cut, such as sintered ceramics.

Using a material similar to diamond as the base body is an effective way to prevent the film from flaking off.

In other words, when sintered diamond is used as a base body, diamond undergoes epitaxial growth, and bonds solidly with the diamond on the surface of the sintered diamond in the case of using a diamond-coated cutting tool with sintered diamond as the base body. This prevents the film from flaking off even when cutting such materials as sintered alumina. Moreover, this process makes the tool far less abrasive than sintered diamond cutting tools.

Thus, using sintered diamond as a base body makes it possible to create a diamond-coated cutting tool with a sufficiently high level of performance. The presence of diamond in the base body is necessary to produce diamond-coated tools that are free from the problem of film separation.

It is thought that it is possible to obtain a diamond-coated cutting tool where there will be no film separation by mixing diamond powder with alumina, silicon carbide, or silicon nitride powder, sintering the mixture, and coating its surface with diamond. In this case, it is necessary to consider the need to provide an intermediate layer such as TiC in order to increase the strength of the bond between the diamond and the ceramic.

In addition to the diamond-coated cutting tool, there is a diamond thin film brazed cutting tool that can be considered to be a cutting tool for the future.

This is to be produced by subjecting a diamond thin plate 0.1-0.5 mm thick to edge processing with a laser or some other device, and brazing it to a molybdenum or ultrahard alloy shank in the form of a bit. It can be said that this will be a very simple, effective method if it can produce a thick, homogeneous diamond film in a short time. Because the edge consists of 100 percent diamond, this tool will be superior in abrasion resistance to a sintered diamond bit containing auxiliary. It also is polycrystalline, and therefore characterized by involving only a small degree of anisotropy of abrasion compared with a monocrystalline bit. According to some reports, there is no need to worry about a shank with a diamond board coming off because of the use of a brazing material containing Ti that is highly wettable with diamond.

It is likely that a tool for ultraprecise cutting, which would be difficult if a coated cutting tool were used, can be produced by brazing a diamond thin plate. What is conceivable as a method for this is to finish the cutting face and flank of a diamond thin plate into a mirror plane measuring about 3 nm Rmax by a polishing method using a thermochemical reaction, and then make it into a cutting tool through brazing. This ultraprecise cutting tool is expected to be used to finish the mirror plane of an aluminum alloy, copper, or the like. As a tool, it will fully use the mechanical and thermal properties of gas phase synthesized diamond, replacing the monocrystalline bit.

2.5.2. Mechanical Seal

In the case of a mechanical seal, a revolving ring fixed to an axis is pressed to a fixed housing ring by using a spring, thereby effecting mechanical sealing in the contact face. The fixed ring and the sliding ring revolve with the same number of revolutions as the axis, while contacting each other. This causes frictional heat, and, moreover, makes it impossible to expect sufficient lubrication or cooling. Therefore, selecting an appropriate sliding material is important, and the contact face must be finished to a highly smooth surface.

Diamond shows a low friction coefficient and high abrasion resistance, strength, and erosion resistance. Therefore, it is most suitable as a sliding material for mechanical seals.

If diamond is to be used as a sliding material, it is necessary to polish the surface very precisely. For this purpose, both the conventional method of lapping with diamond grain or a polishing method using a thermochemical reaction are thought to be effective. When these methods are used, the surface roughness of a diamond film is about 3 nmRa, and the coefficient of friction between the diamond film and the SiC is about $\mu = 0.1$. In this light, it can be said that the polishing process has reached a practical level.

In using diamond as a sliding material for mechanical seals, a process for coating a base body with diamond is conceivable. In this case, the strength of the adhesion between the base body and the diamond becomes a problem.

A sliding ring, unlike the case of a cutting bit, is always pressed from the surface, and strength is added only in a circumferential direction due to axial revolution. Therefore, the problem of separation conceivably can be resolved by devising the shape of the base body by such means as cutting a radial groove to prevent separation due to the force in the direction of revolution. As for prospective materials, those showing a coefficient of thermal expansion close to that of diamond, and a high Young's modulus, such as silicon nitride, are thought to be suitable.

The ring on the other side of the diamond needs to consist of a material having a high degree of abrasion resistance and strength, and one that will not react with the diamond. The most suitable materials include carbites, such as SiC and WC, or nitrides, such as Si_3N_4, BN and AlN.

It is expected that diamond-based mechanical seals manufactured in that way will feature superior heat resistance, erosion resistance, and durability, and will be able to withstand heavy loads. Conceivably, they can be used at places where high reliability is required, and as sealing materials for such equipment as centrifugal separators for uranium enrichment that are used for nuclear power generation.

2.5.3. Slidable, Abrasion-Proof Precision Parts

There are a great many ways of using diamond for precision parts to take advantage of its hardness, abrasion resistance, and low coefficient of friction. We will describe its uses as a protective film for magnetic recording media, and for magnetic heads.

(1) Protective Film for Magnetic Recording Media

Using diamond as a protective film for magnetic recording media is promising in that its abrasion resistance and high lubricity can be utilized in a positive way.

The structure of magnetic recording media and their materials can be grouped in the way shown in Table 2.11.

Table 2.11. Structure of Magnetic Recording Media and Their Materials

	Base board	Method of media formation	Protective film/lubricant
Magnetic tape	Organic film	Coating method/Spattering method	SiO_2/lubricating filmAl_2O_3/lubricating film Carbon deposition, DLC
Floppy disk	Organic film	Coating method/Spattering method	Spattered carbon Al_2O_3, SiO_2
Hard disk	Aluminum substrate Glass substrate	Plating method/Spattering method/Deposition method	Sol gel SiO_2 Spattered carbon DLC, ZrO_2 Si_3N_4

To improve the recording density of magnetic disk media, techniques concerning input and output, that is, those to make the interval between the recording media as narrow as possible, that is, at the submicron level, are required as are improvements in the performance of magnetic recording media themselves.

Figure 2.18 shows the structure of a magnetic head of the Winchester type. Writing to a recording medium is done by magnetizing a magnetic medium layer by the magnetic field leaking from a gap created in the head core. With the revolution of the medium substrate, the magnetic head drags in air between the head and the medium, and obtains a floating force. At the same time, the distance between the head core and the magnetic medium is kept constant through the balance between the floating force and the force with which the head is pressed. To achieve high density recording, efforts are being made to increase the density by shortening this distance as much as possible—to about 0.1-0.4 μm—and by keeping the recording range small by restraining the expanse of the magnetic field leaking from the gap. Figure 2.19 shows the relationships between the track recording density and the degree of flotation of the magnetic head of the disk equipment, the gap length, and the thickness of the medium. To improve track density, these three factors need to be reduced as far as possible.

Figure 2.20 shows changes in gap length and the degree of flotation. It is expected that a flotation height of 0.1 μm or less will be necessary in the future.

The relationship between a magnetic disk and a magnetic head reveals that the floating height of the head is fairly low, even compared to the size of a smoke particle—about 0.1 μm—as shown in Figure 2.21. With regard to the relationship among the disk diameter, the degree of magnetic head flotation over a medium surface, and a disk surface, the relationship between a magnetic head with a floating height of 0.4 μm and a 14-inch disk is often described as "a jumbo plane flying over the ground at a height of 5 mm." This implies that if the disk is equivalent to a lake about 3.7 km across, and if a dust particle bigger than 5 mm is floating on this lake, it would lead to a medium breakdown in terms of a head crash.

The magnetic head touches the surface of the medium every time it stops. This causes friction abrasion, which is repeated many times. This abrasion eventually results in failure due to the appearance of dust. For this reason, technology for producing a magnetic disk protection film is an extremely serious problem.

An ideal material for a protective film must be resistant to abrasion resistance and must provide lubrication. The materials examined to date as protective films are listed in Table 2.12. Spin-coated SiO_2 has been used both because of its performance and ease of production. Reducing the height of flotation will be further promoted for higher density, but various hard materials including carbide and nitride as well as diamond are being explored actively.

Table 2.12. Various Protective Films and Results of CSS Tests (The numerical values show the numbers of sample faces, and the heads used are of the 3340 type)

Protective film material	Method of fabrication	CSS of 10^4 or more possible, no flaw	CSS of 10^4 or more possible, flaw caused	Crash in CSS of 10^4 or less	Crash in CSS of 10^3 or less
SiO_2	RF spatter	8	1	0	0
SiO_2	Spin coated	4	0	0	0
Si_3N_4	RF spatter	4	0	0	0
Rh	Plating	1	5	0	0

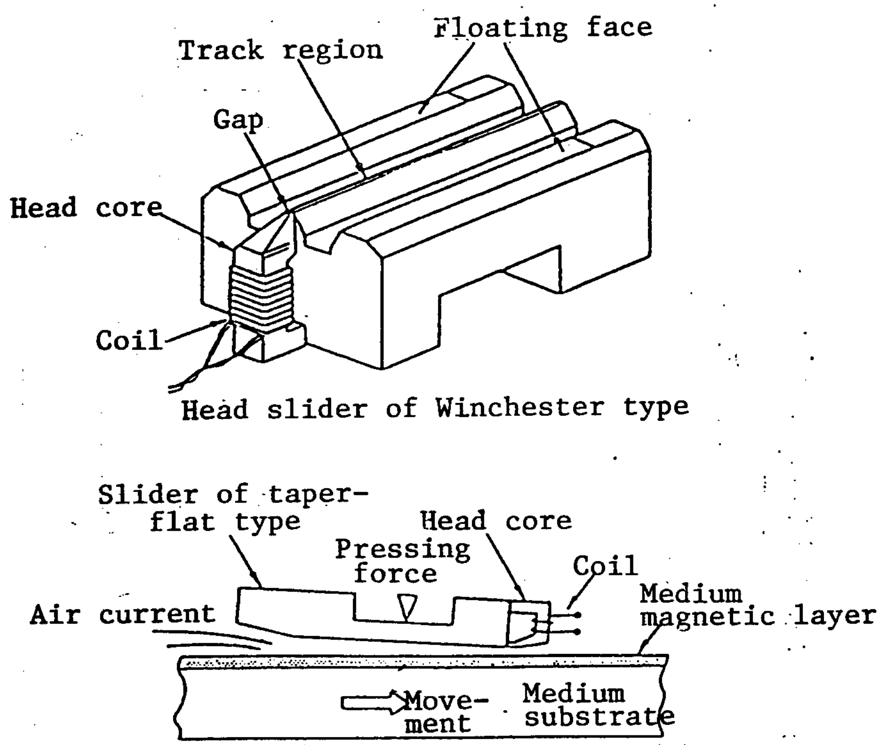

Figure 2.18. Structure of Floating Head

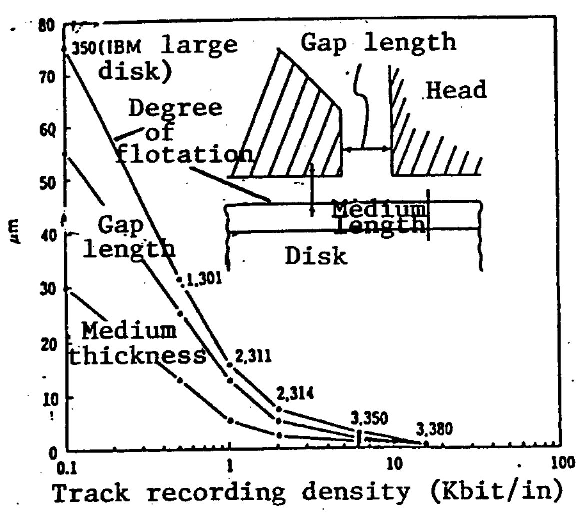

Figure 2.19. Relationship Between Track Density and Principal Parameters

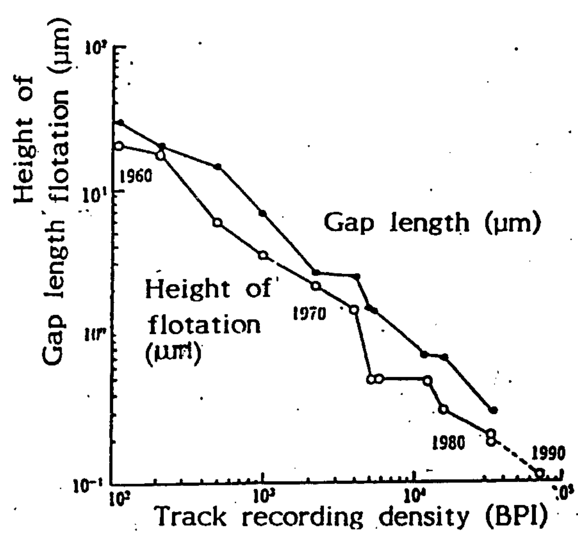

Figure 2.20. Relationship Between Track Recording Density and the Height of Head Flotation

Table 2.12. Various Protective Films and Results of CSS Tests (The numerical values show the numbers of sample faces, and the heads used are of the 3340 type) (Continued)

Protective film material	Method of fabrication	CSS of 10^4 or more possible, no flaw	CSS of 10^4 or more possible, flaw caused	Crash in CSS of 10^4 or less	Crash in CSS of 10^3 or less
Au	Plating	0	6	0	0
Ni-P	Plating	0	0	0	2
Cr	Plating	0	0	0	2
Al_2O_3	RF spatter	0	0	0	2
Toluene-2-isocyanate	Glow discharge assemblage	0	2	1	1
α-hydridon	Glow discharge assemblage	0	2	3	3
Ethylene tetrafluoride	Glow discharge assemblage	0	0	0	2
Propylene hexafluoride	Glow discharge assemblage	0	1	2	0

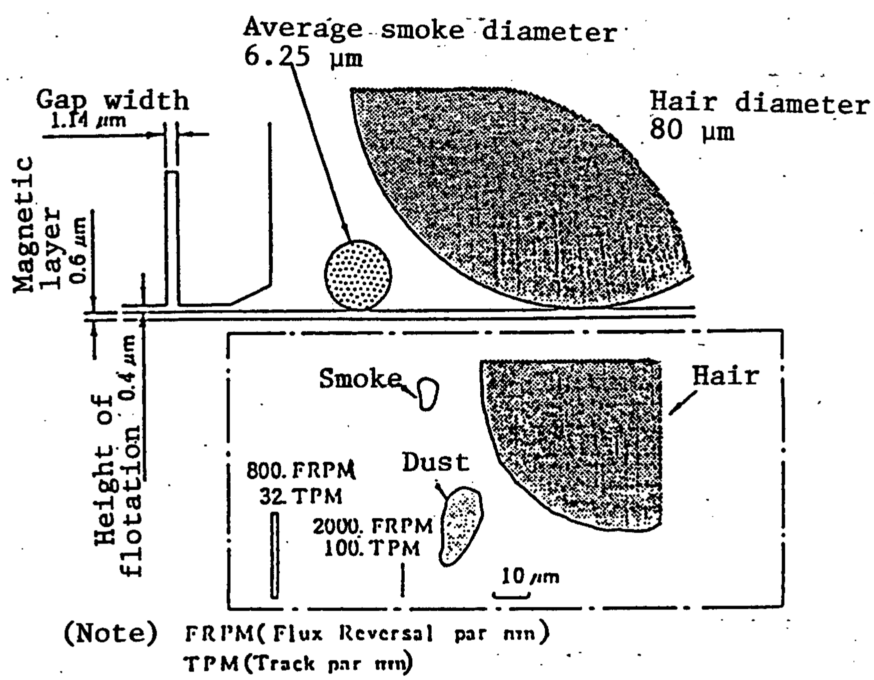

Figure 2.21. Relationship Between Flotation-Type Head and Dust

With regard to the application of diamond for such purposes as magnetic disk protection film, material systems with satisfactory surface flatness, a thickness of less than 100 Angstroms, and a favorable abrasion-proof property are necessary. For this use, new material systems such as DLC need to be developed.

(2) Magnetic Head

To date, there has been no concrete instance of the application of diamond film technology to a magnetic head surface protection film. The mechanical qualities and abrasion-proof property of diamond are in demand for magnetic heads as well, in the same way as was described in the discussion of magnetic medium protection film technology. To date, the abrasion property of magnetic heads has not been clarified.

Figure 2.22 shows the results of a study on the relationship between the degree of abrasion and hardness in audio heads made of glass, Sendust, and ferrite. The illustration shows that the harder a material is, the lower

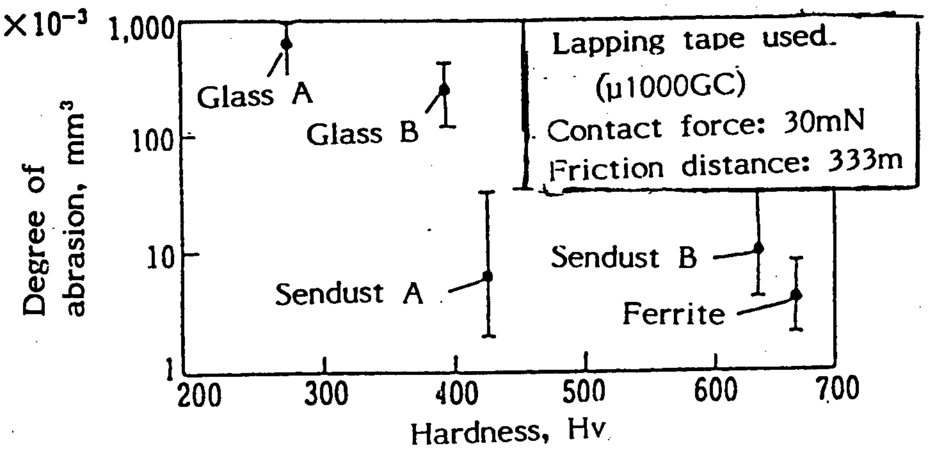

Figure 2.22. Relationship Between Degree of Abrasion and Hardness

the degree of abrasion. The hardness of diamond is Hv = 1,200. Therefore, its degree of abrasion can be estimated to be exceptionally low.

2.6. Applications of Chemical Properties

2.6.1. Plant Parts

Diamond is a very stable material, except that it undergoes oxidation and graphitization at high temperatures, as noted in paragraph 1.7. In the range of normal temperature, it is largely unaffected by highly corrosive chemicals, including nitric acid, aqua regia, and alkali. Because diamond generally has been available only in granular or powder form, there have been few cases where it has been applied in plant parts, except as a composite material, no matter how resistant it is to corrosion. There are cases in which diamond has been used for abrasion-proof parts by sintering a diamond powder with a metal, glass, or ceramic, or by producing a diamond compound through kneading it into plastics or rubber. In fact, however, the corrosion resistance inherent to diamond cannot be fully displayed because the metal or other material used as a binder is chemically inferior in terms of its corrosion resistance.

Even so, now that diamond is being synthesized through gas phase reaction, and now that, moreover, it has become possible to effect corrosion-proof coating internally as well as externally, even over a rather large area, it is likely that diamond will be used for important areas in a plant where corrosion resistance is required. Moreover, self-supporting diamond can be obtained by uniformly separating out diamond in the form of a base material, and then dissolving and removing the base material with acid or the like. Therefore, if this is built in by such means as reinforcement in accordance with any definite purposes, the uses of diamond will expand further.

The technical problem at present is that the degree of freedom in the base material on which diamond is to be separated out is not sufficient because of such factors as the difference in thermal expansion coefficient and reactivity with carbon. To cite a simple example, diamond cannot be directly separated out on steel or stainless steel, which are widely used for plant members. In addition, although the diamond is to be placed over a wide area, currently it can be used to cover only areas measuring several centimeters in diameter, which is still short of a practical size. However, chemical reaction equipment, which consists of a diamond or diamond-coated reaction receptacles and pipe, will appear through technological improvement and through progress in the development of diamond-like carbon, although its physical properties have not yet been fully elucidated.

Another way of using diamond as plant parts is by causing it to display its two characteristics—erosion resistance and abrasion resistance. Lining for corrosive slurry that contains solid matter is a good example of a potential application. Using diamond for the eyeholes of reaction receptacles and so forth also is promising. In particular, diamond transmits light in a wide wavelength band, except in the neighborhood of 5 μm. Therefore, it could be developed not only for mere internal observations but also for a higher degree of applications including internal examinations using infrared rays.

Receptacles for superhigh-purity corrosive chemicals such as H_2SO_4 are an example of diamond applications that currently are being actively pursued. In the future, there will be increasing attempts to develop high-purity or superhigh-purity chemicals, even in fields other than semiconductor resolution. Therefore, using diamond because of its corrosion resistance also is thought to be important.

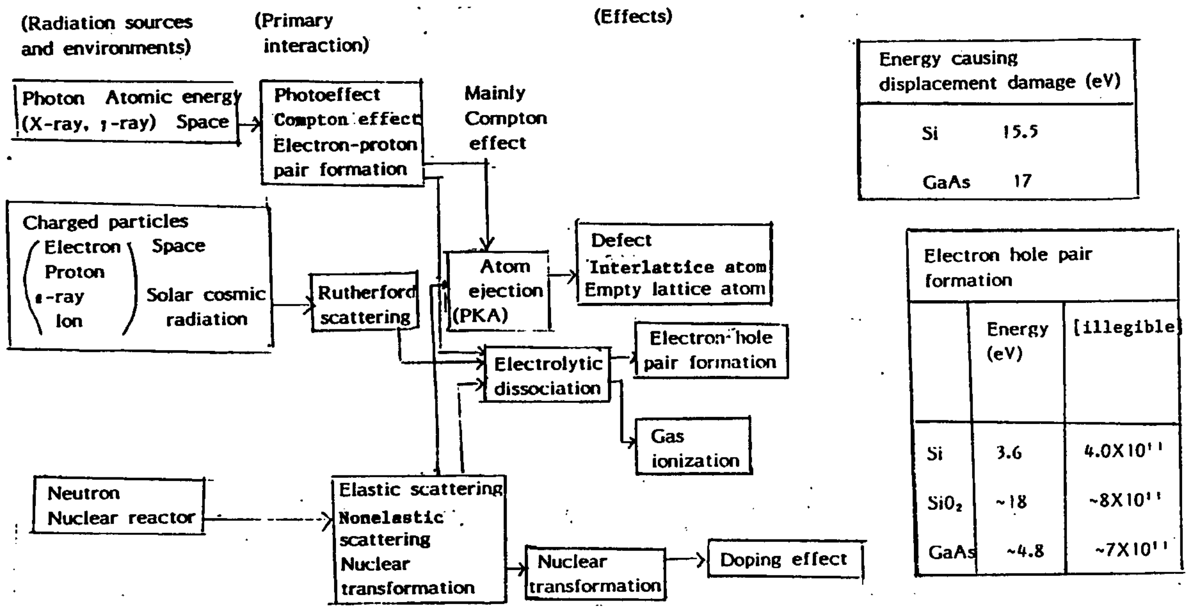

Figure 2.23. Basic Effects of Radiation on Semiconductors

2.6.2. Environment-Proof Parts

2.6.2.1. Radiation-Proof Coating

It is hoped that semiconductor devices can be developed that will be usable in the space environment, where they will encounter space cosmic rays, for such devices as artificial satellites, planet probes, space bases, and so forth. It also is hoped that such devices can be used in severe radiation environments, as in the case of robots for nuclear reactors.

After radiation passes a structure 1.8 mm thick, the Al body of a geostationary satellite, for example, the inner parts are subjected to secondary radiation including γ rays at a rate of more than 4.5 x 10_5 rad (Si) for 10 years. Also, in the case of sensors used for the inspection and maintenance or robots at a nuclear power station, an element having a resistivity of more than 10^6-10^8/cm^2-s for γ rays is required.

Radiation can be roughly grouped into three categories—electromagnetic waves, that is, photons, represented by γ-rays and X-rays; charged particles, represented by electrons and protons; and neutrons. The basic effects of these kinds of radiation on semiconductors are shown in Figure 2.23.

Further, the effects of radiation can be roughly grouped into the following two categories according to changes in device property, as shown in Figure 2.24:

(1) Total dose effects causing semipermanent property deterioration due to regular electrolytic radiation (γ-rays, etc.) laid down in terms of the dose absorbed (rad).

(2) Transient dose effects causing temporary malfunctions (soft errors), permanent breakdown, or latchup due to transient large-dose irradiation laid down in terms of absorbing dose rate (rad/s) or high-energy particles (α-rays, etc.).

Measures to strengthen radiation resistance can be roughly grouped into four categories: 1) improving element manufacturing processes, 2) strengthening element structures, 3) circuit configuration, and 4) materials selection. These measures vary depending upon whether they are for total dose effects or for transient dose effects.

For example, materials with an inherently short minority carrier life and high mobility, together with epitaxial substrates with few defects, are used to cope with defects caused by radiation. In the case of diamond, both positive holes and electrons have high mobility compared to silicon. Thus the use of diamond should make it possible to fabricate devices that are largely free from defects caused by radiation.

2.6.2.2. Ultraviolet Sensor

(1) Physical Properties of New Diamond and Ultraviolet Sensor

Diamond is a heatproof material with a wide band gap of 5.47 eV. It also is known as a radiation-proof material.

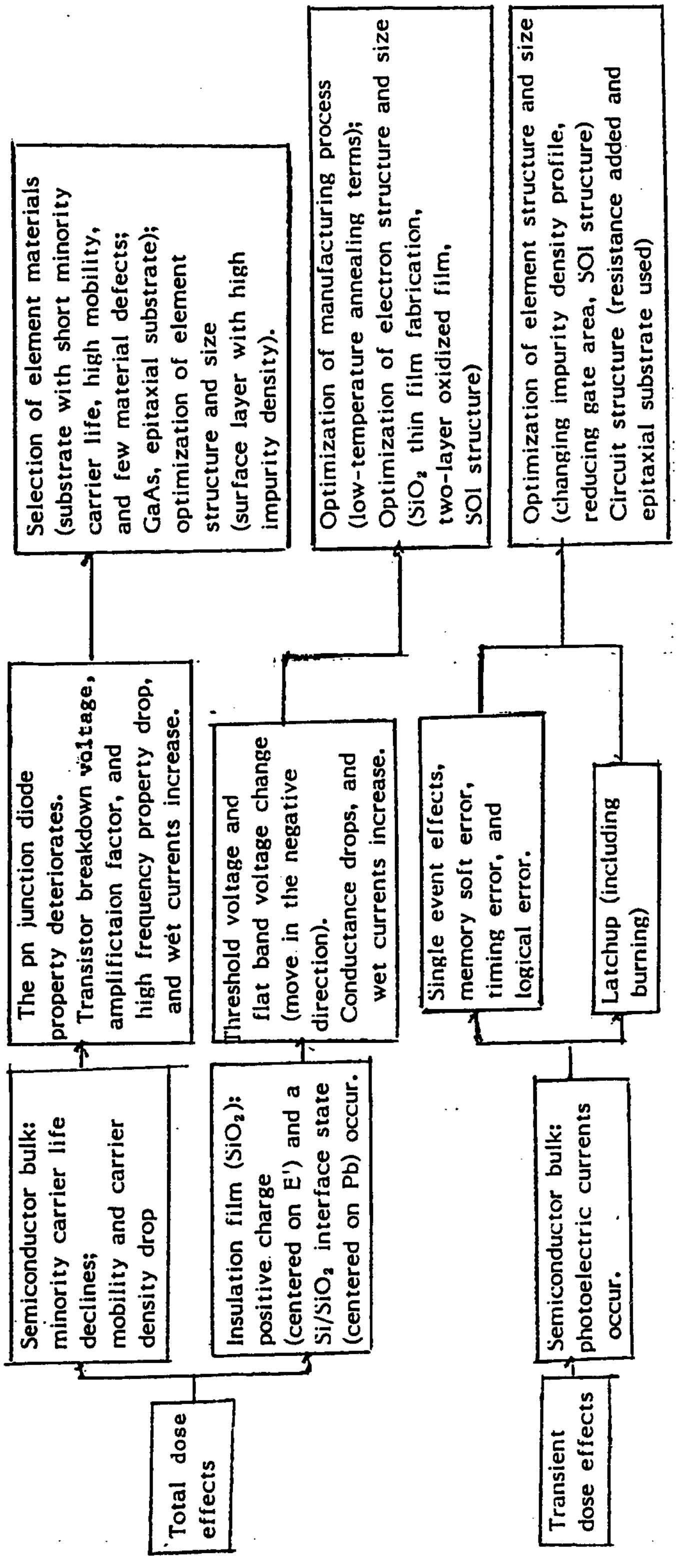

Figure 2.24. Effects of Radiation and Countermeasures

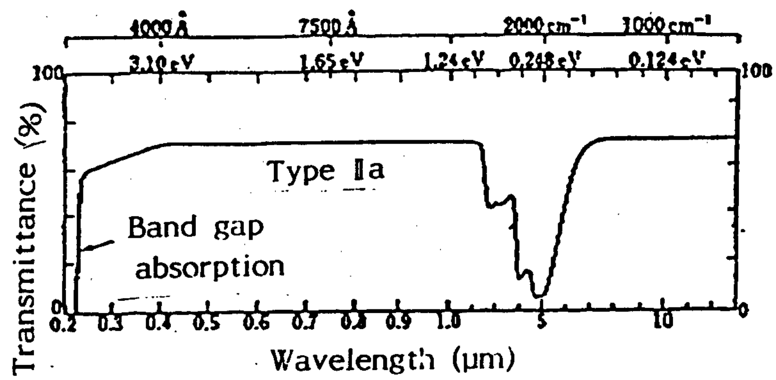

Figure 2.25. Optical Transmittance of Low-Pressure Gas Phase Synthesized Diamond

From an optical point of view, the wide band gap means that diamond is transparent as far as the ultraviolet region with a short wavelength. Figure 2.25 shows the light transmission spectrum of an artificial diamond. The shortwave absorption edge changes due to impurities in the diamond, but gas phase synthesized diamond (II a) is transparent as far as the 200 nm band.

At the same time, however, the increase in the number of ultraviolet rays due to the breakdown of the ozone layer caused by fluorohydrocarbons, and the accompanying increase of such diseases as cancer, are cited as problems related to the preservation of the global environment. Therefore, worldwide observation of ultraviolet ray and ozone densities over the earth's surface, both in the convection sphere and in the stratosphere, is an urgent task.

To observe ultraviolet ray and ozone densities, spectroscopic systems loaded with (1) photoelectromotive force-type sensors such as photodiodes, and (2) photoelectron emission-type sensors such as photoelectric tubes, are used in the ultraviolet ray region. (Ozone density is to be observed from light absorption of wavelengths in the neighborhood of 254 nm.)

In this case, the II a new diamond produced by low-pressure gas phase synthesis probably will be effective as a window material for a spectroscopic system requiring transparency in an ultraviolet range up to the 200 nm band.

What is more interesting is that a diamond photodiode will be produced by using new diamond that is to be turned into a semiconductor by such means as boron doping. This suggests the possibility of realizing a photoelectromotive force-type sensor that will be superior in heat resistance to the current Si or GaAs photoelectromotive force-type sensor. This new sensor also will be stable in space.

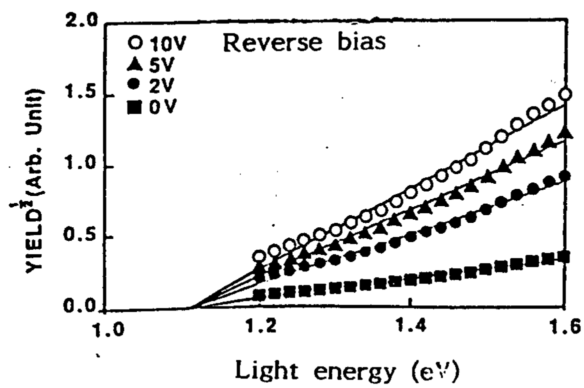

Figure 2.26. Photodiode Properties [Au (16 mm)/diamond film (20 μm)]

(2) Example of Photoelectromotive Force-Type Sensors

Figure 2.26 shows the light responsive properties of a Schottky diode with a gold-diamond structure formed by the CVD method. Strong light responses are apparent, showing the possibility of realizing a photoelectromotive force sensor based on this kind of diode.

(3) Future Development

Ultraviolet or ozone sensors are loaded in artificial satellites and placed above various parts of the world to carry out earth observations relative to the preservation of the global environment. However, current sensors are heavy, weighing tens of kilograms. Therefore small, light sensors are being sought. Sensors are also required to be self-cooled without using the artificial satellite itself as a heat sink.

A highly integrated sensor using heatproof diamond will be indispensable for meeting such requirements. In such a sensor, the sensor region, the signal processing region, and also the actuator region must be integrated.

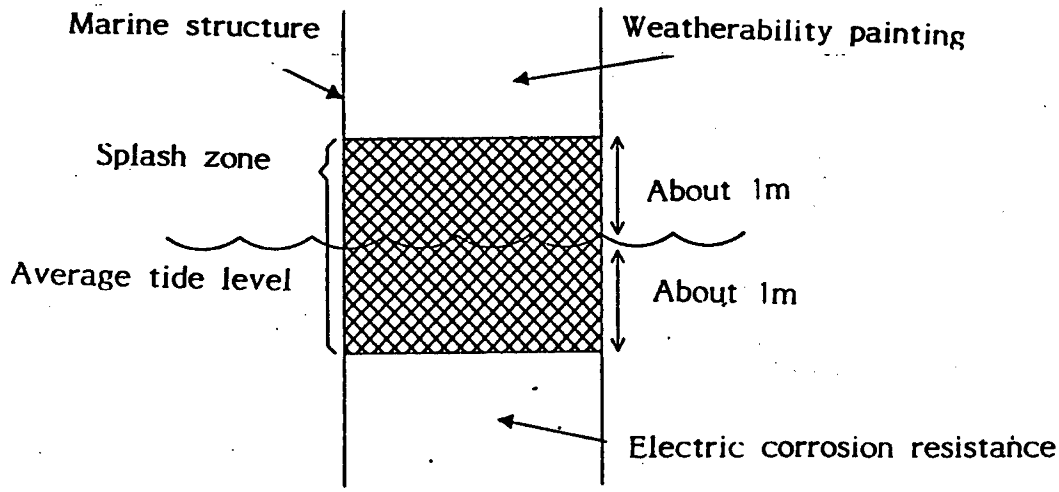

Figure 2.27. Marine Structure in the Vicinity of the Surface of the Sea

2.6.2.3. Marine Environment

Weatherability (resistance to ultraviolet rays) and corrosion resistance (impervious to rust) are important properties required of the surfaces of structures in the marine environment. Usually, weatherability is important for a part exposed on the surface of the sea, while erosion resistance is important for a part submerged under the sea surface. Currently, the problems involved in the structures on the surface of the sea and those involved in structures under the sea surface have been settled for the most part through high-weatherability painting technology and electric corrosion-proof technology, respectively.

However, the area (splash zone) about 1 m above and below the average tide level causes a large degree of corrosion, as shown in Figure 2.27. Sufficient countermeasures do not exist at present. Devices that must operate in this zone are subject to irradiation by ultraviolet rays while being submerged in sea water. They also can be shocked by an object floating on the sea. Therefore, a surface treatment that meets the following three conditions for performance is necessary:

(1) Weatherability (resistance to ultraviolet rays);

(2) Corrosion resistance (will not rust or permit local progress in rusting);

(3) Shock resistance (no damage will occur if it strikes an object).

The splash zone is currently dealt with by winding something hard (lining), but this is not fully satisfactory.

Therefore, a diamond coating is worthy of study as a surface processing material that meets the three conditions set out above.

Diamond is known to provide superior radiation resistance. (1) Its weatherability is thought to be satisfactory, and it is also known to be superior in resistance to chemicals including acids and alkalis. (2) Its corrosion resistance is thought to be satisfactory. However, a coating film must be so elaborate that the base material is not exposed at all. (3) Given its high degree of hardness, diamond might meet the need for shock resistance if its bonding strength is sufficiently great.

To realize these goals, two additional points are required:

(4) Capability of being repaired (under water, if possible), and (5) capability to apply a coating, even on rust.

Ships that are processable in a dock, for example, can easily be given a surface treatment, but marine structures at large are left alone on the sea semipermanently. Therefore, the fourth point, the capability of being repaired, is important. If there is any dust present, a coating can be applied only after it is removed. But when the rust cannot be fully removed, it is left as is in the course of coating. Therefore, the fifth point, the capability of coating with a high degree of adhesion even on rust, is important.

Thus, we have described the possibilities for applying diamond coating to marine structures. [passage omitted]

3.2. Current Status of Technologies for Using Diamond Functions for Substances Other Than Semiconductors, and Associated Tasks

3.2.1. Optical Parts

The performance levels required of optical parts are listed collectively in Table 3.8.

Table 3.8. Performance Levels Required of Optical Parts

	Uses		
Items required	X-ray parts Window, mask	Infrared ray parts Window	Laser parts Ultraviolet ray transmitting window
Range of wavelength (Not less than 70% transmittance)	About 40 Angstroms	About 50 μm	200-300 nm
Size (mm), diameter thickness	100 φ 0.5-1 μm	70 φ 1-3 mmt	100 φ
Intensity Shock resistance Bend resistance	Differential pressure 20 mm Torr	Vacuum resistance	High pressure resistance 2 Kg/cm^2
Damage resistance	X-ray damage resistance	Heat resistance	Laser damage resistance

In applying diamond for optical purposes, there are instances where it has been used in bulk, like a window material, and also for thin film coatings, as in the case of a reflection preventing film. Applications that are currently anticipated include (1) window and mirror materials for optical use, (2) reflection preventing film, and (3) optical fiber coating. In all cases, it is necessary to ensure that the optical properties of the materials are uniform, and to reduce the amount of impurities. In the case of a polycrystalline diamond thin film, optical anisotropy occurs when the grain boundary involves any impurity, nondiamond phase, distortion, or the like.

(1) Window and Mirror Materials for Optical Use

These materials already have been described in paragraph 2.2.3. When polycrystalline diamond film is used for these purposes, the flatness of the film surface poses a problem, and the film must be flattened by such techniques as mechanical polishing or ion milling. When the wavelength to be used is more than 10 μm or so, no serious problems will arise even if there is unevenness measuring about 0.2 μm on the film surface.

In the case of a high-output laser, changes in the quality of materials due to optical breakdown, thermal shock, heat, and corrosion due to the plasma come into question, but diamond is very resistant to all of these.

(2) Reflection Preventing Film

Ordinary reflection preventing films include Al_2O_3, CaF_2, and TiO_2. However, coating with a diamond thin film is effective not only for a reflection preventing film, but also serves to prevent surface damage and to restrain uneven temperature distribution in window materials. Because diamond shows a high refraction index, it produces the same effect as other materials when applied as a thin coating.

(3) Coating of Optical Fibers

Because diamond is hard and highly resistant to chemicals, coating optical fibers with it makes it possible to prevent chemical changes due to surface damage or humidity.

To make it possible to use diamond as an optical window material, it is desired that the following tasks be fulfilled:

(i) Material properties: The basic optical properties of diamond have nearly reached a practical level. Because gas phase synthesized diamond is polycrystalline, it produces greater effects than single-crystal diamond with regard to scattering or absorption due to defects or impurities. These effects have not been investigated fully.

(ii) Area expansion: To use diamond as a window material, a minimum size of 100 mm φ is necessary. Given the current level of technology, this is thought to be nearly on a practical level. Hopefully, however, area expansion to a meter size can be achieved.

(iii) High-speed film fabrication: To make it possible to use diamond as a window material, it also is necessary that sufficient mechanical strength be realized. Current technology has not yet reached the point of obtaining a window material with sufficient thickness. To use diamond as a window material, a technology to obtain 100 μm/hour or so is necessary. It is hoped that the speed can be further increased by more than one order of magnitude.

3.2.2. Thermal Parts

3.2.2.1. Heat Sink

Nitric impurities are among the factors that influence the thermal conductivity of single diamond crystals. With regard to natural diamond, a detailed study by Bergmeister shows that its thermal conductivity drops as the total amount of nitrogen increases. In the case of high-pressure synthesized single crystals, the same level of thermal conductivity as that of natural, high-purity single crystals has been obtained by controlling the amount of nitrogen.

Ordinary diamond contains a 1.1 percent carbon isotope (^{13}C), and it is believed that this is one of the factors that causes phonon scattering. To date, however, it has been assumed based on theory that the difference in ion radius is far smaller than in the case of nitrogen, and it has been estimated that the effect of this isotope on the thermal

conductivity of diamond is several percent at most. Recently, Anthony and others have synthesized microscopic diamond by the CVD method using 99.9 percent ^{12}C content methane as a raw material. With this diamond as a raw material, they synthesized a less than 1 carat single crystal under superhigh pressure and measured its thermal conductivity. Table 3.9 shows its values. Diamond with ^{13}C reduced to 0.07 percent shows at normal temperature a thermal conductivity 1.5 times as high as ordinary, high-purity diamond. In view of the relationship between thermal conductivity and ^{13}C density, they suggest that thermal conductivity could be increased by a factor of two.

Table 3.9. Thermal Conductivity of Synthesized Diamond Single Crystals With Different ^{13}C Isotope Content, and of Other High-Radiation Materials

Material	Thermal diffusivity ($cm^2 s^{-1}$)	Thermal conductivity ($W cm^{-1} K^{-1}$)
0.07% ^{13}C diamond (this work, enriched)	18.5	33.2
0.5% ^{13}C diamond (this work, enriched)	14.5	26.0
0.1% ^{13}C diamond (this work, natural abundance)	12.4	22.3
Natural diamond (this work)	12.2	21.9
CVD diamond		12.0
Cubic boron nitride		7.6
Silicon carbide		4.9
Copper	1.25	4.0
Beryllium oxide		3.7
Boron phosphide		3.6
Aluminum nitride		3.2
Silicon	0.86	1.6
Aluminum oxide		0.2

Measurements of the thermal conductivity of materials with high thermal conductivity reveal many points to be explored with regard to reliability. If that report is true, it will be necessary to re-examine the conventional theory of thermal conductivity.

With regard to the thermal conductivity of gas phase synthesized diamond, a value estimated at about 50 percent of the conductivity of high-purity single crystals has been reported, as additionally described in Table 3.9. Because this is a polycrystalline film, phonon scattering caused by the grain boundary is probable, but there are many points to be explored, including measurement methods to determine the presence of impurities such as hydrogen, nitrogen, and nondiamond carbon. Figure 3.34 shows the most recent data on gas phase synthesized diamond thick films. In the case of gas phase synthesized diamond film, which is evaluated by Raman spectroscopy, when nondiamond carbon is not present, light penetrability is high and thermal conductivity shows an improvement. In any case, it is necessary to clarify the factors that hinder the thermal conductivity of gas phase synthesized diamond, for example, by evaluating the effect of temperature all the way down to extremely low temperatures.

Superhigh-pressure synthesized diamond single crystals are currently used for some kinds of heat sinks for semiconductor lasers. However, for a number of reasons, including a drop in threshold electric current for semiconductor lasers, there are few cases where diamond sinks are needed. If an inexpensive thick film with a high level of thermal conductivity becomes obtainable through gas phase synthesis, the range of applications will expand. To this end, it is necessary to improve their properties, as compared to single crystals. In addition, it will be necessary to secure a larger area for high-quality diamond film and to develop techniques for high-speed analysis. As for heat sinks, properties other than thermal conductivity, such as the dielectric constant and the dielectric loss factor, are also important, but virtually no

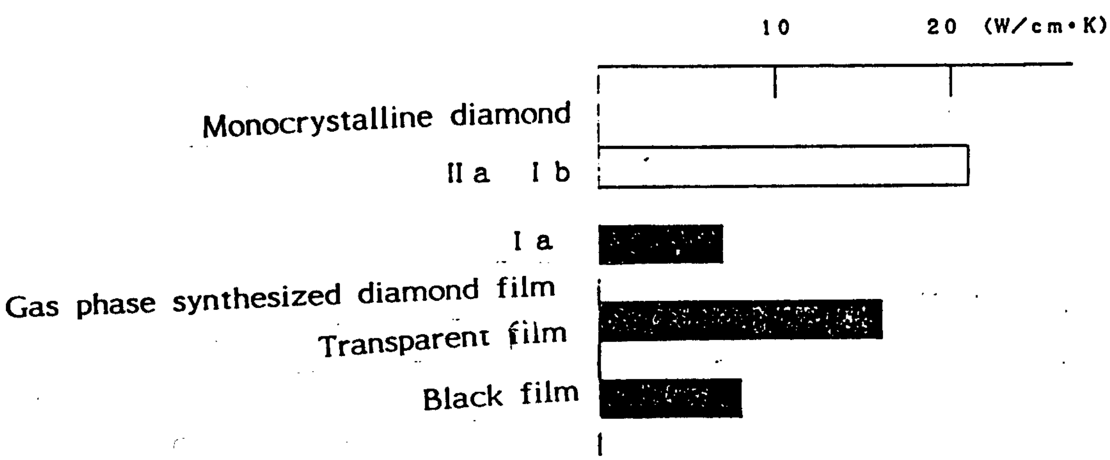

Figure 3.34. Thermal Conductivity of Gas Phase Synthesized Diamond and Monocrystalline Diamond

studies have been made on these subjects. These properties also need to be clarified in connection with film quality.

3.2.2.2. IC Substrate

If diamond is to be used as a material for IC substrates, it is necessary to consider using it not only as a simple substance, but also combining it with other materials including organic materials such as polyimide, or with quartz, etc. In any case, it is conceivable that diamond can display the greatest advantage in technologies for using materials in the form of a large-area film.

The technical tasks necessary to put diamond into practical use as an IC substrate material are as follows:

(1) Area expansion: Currently it can be proved that a 4-6 inch range is possible, but a technique to further increase the area is absolutely necessary.

(2) High thermal conductivity: The high thermal conductivity of a diamond thin film is well known. Techniques to further improve the qualities and properties for higher uniformity, fewer defects, and so forth, are thought to be a future task.

(3) High-speed film fabrication: To use diamond for IC substrates, a minimum thickness of 1 mm or more for the diamond layer is necessary in view of its mechanical strength, handling property, and so forth. For this purpose, 100 μm/hour is desirable.

(4) Metallized film adhesion: For multilayer wiring substrates, not only diamond but also a diamond film fabricated on a metal wiring layer is necessary. Currently there is no satisfactory method for achieving adhesion between a metal and diamond. A Ti/Pt/Au structure ordinarily is used, but a new metallizing system must be developed for a multilayer structure consisting of diamond and a metal.

(5) Low-temperature film fabrication: A technology for low-temperature, high-speed film fabrication is required, particularly for the realization of laminate devices. Currently, the need for a high temperature exceeding 800°C is a big barrier. As an ideal temperature, 500°C or below is desirable.

(6) Low thermal distortion: Considering the field where diamond is to be used for composite functional materials, including diamond-metal wiring, metallization, and bonding to silicon devices, it is necessary to develop a material system that conforms to the thermal expansion coefficient of diamond. [passage omitted]

3.2.4. Current Status of Mechanical Parts, and Tasks

3.2.4.1. Coated Cutting Tools

Diamond is a hard material that is thermally conductive. It can be processed into a sharp edge, and offers superior abrasion resistance and deposition resistance. In light of these superior properties, diamond-coated cutting tools are produced by coating the bit-shaped surface of a base material with a diamond film. It is expected that such tools will serve to improve processing accuracy in cutting nonmetal materials, and to prolonging the life span of tools. Ceramic materials with a high Young's modulus, such as ultrahard alloys and silicon nitride, are used as base materials.

The big problem with diamond-coated cutting tools is the strength of the adhesive bond between the base material and the diamond. Diamond does not attain epitaxial growth on a different kind of base material. Its growth takes place after nuclear formation on the surface, and then it is turned into a film. To increase the adhesive strength, therefore, it is necessary to raise the density of nuclear formation, use a base material whose thermal expansion is similar to that of the diamond, or use a base material that attains epitaxial growth.

When an ultrahard alloy is used as a base material, the strength of the adhesion to the base material can be improved by increasing the density of the nuclear formation or the strength of the mechanical bond. This in turn can be achieved by causing distortion by such means as removing carbon or cobalt from the surface of the base material and then synthesizing diamond on it.

Silicon nitride has a coefficient of thermal expansion that is close to that of diamond. Therefore, it is advantageous in that it will not flake off due to a difference in this coefficient. The density of nuclear formation can be increased by injuring the surface so that the degree of adhesion can be enhanced.

Diamond coated cutting tools are used to cut nonferrous metals such as aluminum and copper alloys, carbon, FRP, FRM, and C-C components.

With regard to the cutting of aluminum alloys, the diamond film will not flake off when the silicon content reaches 12 percent, showing that its cutting performance is stable. When the silicon content is as high as 24 percent, however, the film flakes off. Figure 3.44 shows the results of cutting a hyper-eutectic Al-24 percent Si alloy by a cutting tool consisting of a silicon nitride base material coated with diamond. When the depth of cut is great, the film flakes off at a cutting distance of less than 1,000 m.

Thus, a diamond-coated cutting tool that uses a base material that is different from diamond in terms of quality involves the problem of film flaking, and it is difficult to use this tool for materials that are difficult to cut, such as sintered ceramics.

To prevent the diamond film from flaking off, it is necessary to use a base material having the same qualities as diamond. When sintered diamond is used as the base material, the diamond grows epitaxially on the surface of the sintered diamond, and they bond together solidly. Figure 3.45 shows the results of experiments in cutting sintered alumina by using a diamond-coated cutting tool in which sintered diamond is used as the

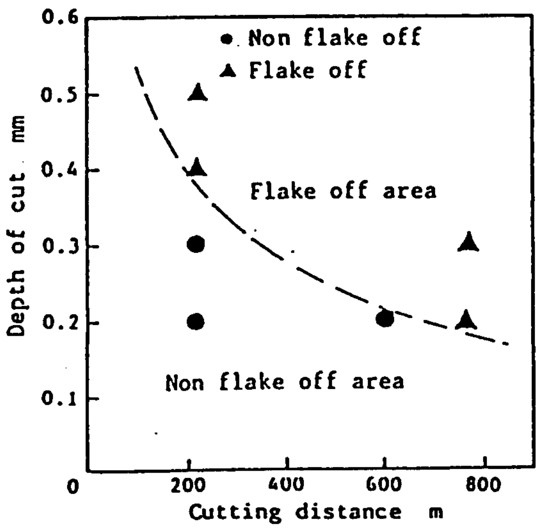

Figure 3.44. Performance of a Diamond-Coated Cutting Tool Used To Cut an Al-24 Percent Si Alloy

base material. For a diamond-coated cutting tool, the film does not flake off, and, moreover, there is very little wear compared to a cutting tool where sintered diamond is used as the base material. Thus, this tool is found to be fully usable as a cutting tool for ceramic materials.

Here we have introduced the current status of diamond-coated tools, and have classified them into two groups, one in which the base material is of the same kind as diamond, and a second in which the base material is different in kind from diamond. When sintered diamond is used as the base material, there is no fear of the film flaking off, but to do so is problematical in that shaping the base material into complex forms is difficult, and the cost is high. When a base material different in kind is used, there is the problem of the film flaking off. It is hoped, however, that the strength of the chemical and mechanical bond between the film and the base material will be improved.

3.2.4.2. Mechanical Seal

In designing revolving equipment where a liquid will be used, it is necessary to use an axis sealing device. Mechanical seals are preferable to other methods such as an oil seal, because they can withstand high speeds and temperatures, have a long operational life, and do not cause the axis to wear away. For these reasons, mechanical seals are used for many purposes.

As shown in Figure 3.46, a mechanical seal is effected by pressing a revolving ring fixed to an axis against a housing-fixed ring by means of a spring, and producing a mechanical seal in the contact area. The sliding surface must be finished with a flatness of less than 0.9 μm and a surface roughness of less than 0.2 S. It is usually finished and processed through honing or superfinishing.

The fixed ring and the sliding ring give rise to frictional heat because they revolve with the same number of revolutions as the axis while contacting each other. Moreover, sufficient lubrication and cooling cannot be expected. Therefore, it is important to select appropriate sliding materials.

Among the currently available sliding materials, graphite, which offers superior abrasion resistance and is self-lubricating, generally is used on one side. The graphite currently used can be grouped roughly into the following three categories:

(1) A sintered body consisting of graphite only.

(2) A graphite sintered body impregnated with resin, metal, or wax like in the pore region; the binder is vapored after the graphite powder has been sintered together with the binder.

(3) A mold produced by pressing graphite powder together with a resin or metal.

The sintered body consisting of graphite only is superior in strength and thermal conductivity, but it is difficult to do without the pore. Therefore, the impregnated graphite sintered body is used in many cases. The pressurized mold can be produced easily, but it is inferior in terms of mechanical strength, and is therefore used only for light loads.

For the side of the ring that slides against the carbon ring, a material that features superior abrasion resistance, strength, corrosion resistance, and thermal conductivity is required. Among the materials used as single substance are such metals as hardened steel and cast iron, and ceramics consisting of alumina, zirconia, or superhard alloys. These ceramics are superior in abrasion and corrosion resistance, but inferior in shock resistance and processibility. Therefore, a metal material that is both abrasion and shock resistant, and is then coated with a ceramic material consisting of alumina, zirconia, or the like, has come to be used recently.

Diamond, which has a low friction coefficient and features superior abrasion resistance and hardness, is thought to be highly suitable as a sliding material for mechanical seals. However, there is no detailed report on the application of diamond to mechanical sealing, except on the use of shock-synthesized diamond powder.

Gas phase synthesized diamond is currently evaluated as an abrasion-proof material, and its application to mechanical sealing is anticipated.

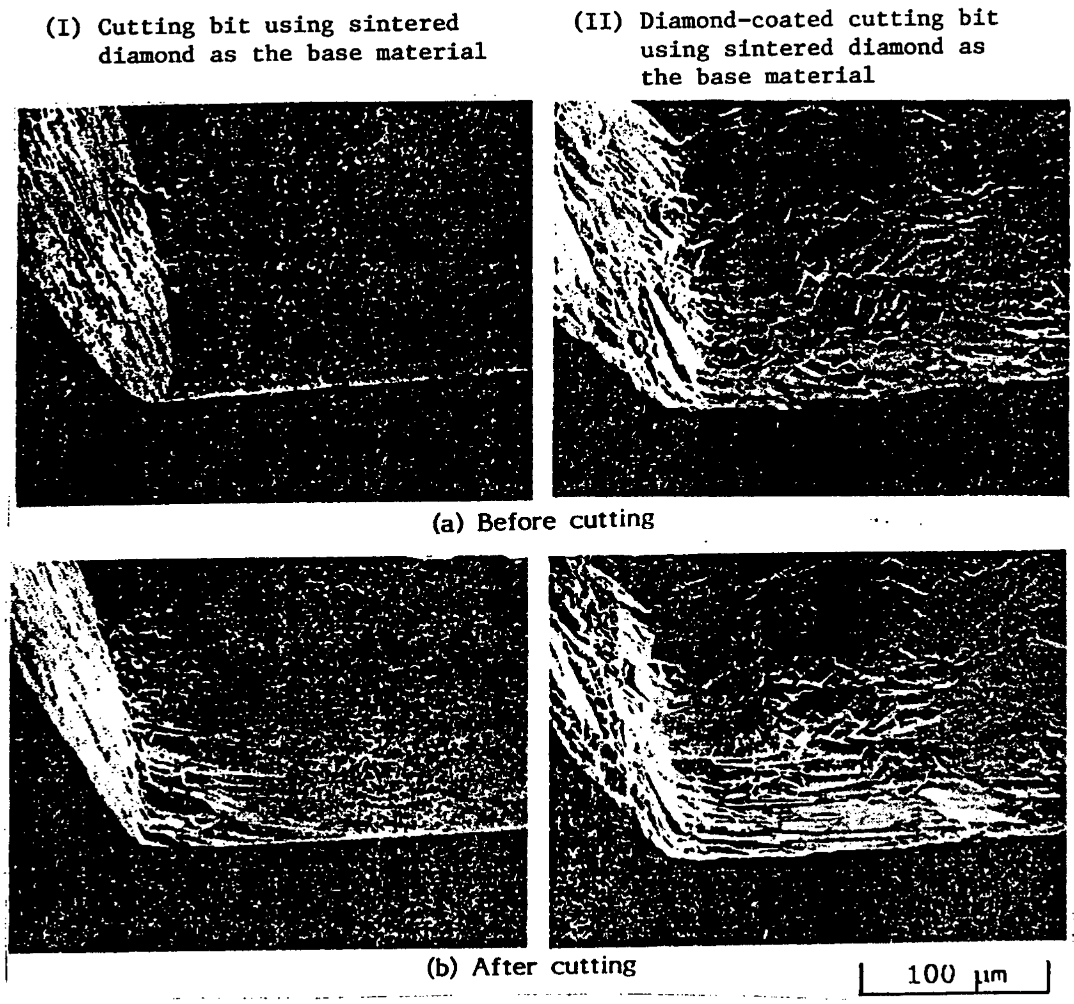

Figure 3.45. Results of Cutting Sintered Alumina With a Diamond-Coated Cutting Tool Using Sintered Diamond as the Base Material (state of abrasion at the bit edge due to cutting)

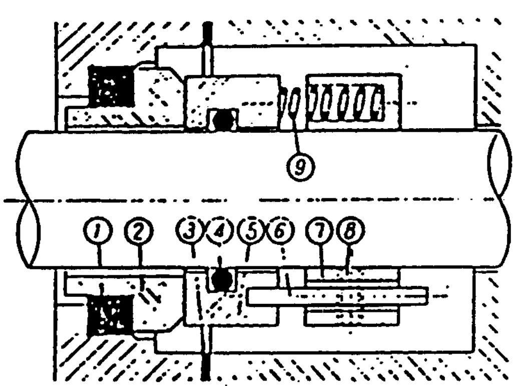

Figure 3.46. Rough Sketch of a Mechanical Seal

(1) Buffer ring; (2) Fixed ring; (3) Gasket; (4) O ring; (5) Revolving ring; (6) Whirl-stop; (7) Revolving ring; (8) Fixed screw; (9) Spring

3.2.4.3. Precision Mechanical Parts

Evaluation items required for the application of diamond in mechanical parts are listed collectively in Table 3.13.

Surface flatness, which is most strict in the case of a surface protecting film for magnetic disks, needs to be below 50 Angstroms.

Among protective film materials, there currently is no material that features either abrasion resistance or lubricity. For films that are not only hard but also adhere to the base board and are self-lubricating, and also for magnetic disks and so forth, a flatness on the order of Angstroms is required for the surface.

From the viewpoint of diamond synthesizing technology, it also is necessary to engage in technological research from a practical point of view, including techniques for high-speed and low-temperature film fabrication; for controlling lubrication, abrasion resistance, and corrosion resistance; and for synthesizing films that are of the finest possible structure and that are highly adhesive to the base board.

Table 3.13. Various Applications and Evaluation Items

	Desks, beds	Tools	Sliding parts
Surface flatness	[double circle]	o	[double circle]
Thin film fabrication (<1 µm)	[double circle]		
Thick film fabrication			o
Abrasion resistance	[double circle]	[double circle]	[double circle]
Hardness			
High lubricity	[double circle]		[double circle]
Friction coefficient			
Corrosion resistance	o	[double circle]	o
Chemicals, humidity			
Corrosion glass			
Adhesion	[double circle]	[double circle]	[double circle]
Toughness		[double circle]	
Heat resistance		[double circle]	o
Young's modulus		[double circle]	
Thermal conductivity	o		

3.2.5. Corrosion- and Environment-Proof Parts

3.2.5.1. Current Status and Future Perspectives

It cannot yet be said that techniques for using diamond for corrosion- and environment-proof parts have been established. Therefore, we will here point out the possibilities for the application of diamond rather than considering the present situation, and will see how far we have to go to reach the application stage.

With regard to parts that are resistant to corrosion and the environment, the following items are conceivable:

(1) Plant parts
(2) Radiation resistance
(3) Ultraviolet rays
(4) Marine environment

With these items as key words, we can think of the following possibilities:

1) Corrosion-proof and weather-proof coating for land-based plants;

2) Electron devices that are resistant to severe environments (places exposed to high temperatures, chemicals, etc.);

3) Vessels that are resistant to chemicals;

4) Radiation-proof devices for use in space, nuclear reactors, etc.;

5) Radiation-proof sensors;

6) Ultraviolet-proof sensors;

7) Weather-proof, corrosion-proof, and shock-proof coating for marine structures.

To put parts realizing these potentials into practical use, however, the following problems must be overcome:

i) Data on the corrosion, weather, and shock resistance of diamond are insufficient.

ii) Techniques to using diamond in electronic devices are only in the development stage.

iii) There are as yet no means for rapidly fabricating fine, highly adhesive diamond films that can cover an area large enough to make them applicable to plant parts.

iv) Data on irradiation effects are insufficient.

v) When maintenance is taken into consideration, it is desirable that coating can be effected even under unfavorable environments, but no techniques to make this possible have been established.

vi) There is a limit to producing the base materials that make coating possible.

vii) Some of these applications are difficult to realize when the cost is considered.

However, if only some of these problems are solved, it may prove possible for these applications to be realized at an early date. If great progress is made in semiconductor technology in particular, it is likely that ultraviolet sensors and similar devices can be produced in the near future.

3.2.5.2. Plant Parts

To date, diamond has never been used for plant parts. However, it has become possible to do large-area coating by the CVD method, and techniques have been developed to separate diamond out, put it on a dome-shaped

or pipe-shaped base board, and then make it independent through removing the base board. Therefore, we think it will not be long before diamond gradually begins to be put to practical use as plant parts. We will comment on some parts that may be able to use diamond.

(1) Peepholes

Diamond film cut from a single crystal currently is used for the sensor windows of Venus probe ships. However, if wide-area diamond coating becomes possible, diamond film could be fitted in peepholes in any part of a plant where abrasion and erosion resistance is required. One conceivable method involves separating diamond out and putting it on a base material that transmits light at a given wavelength, including visible light, or to stick independent diamond to a base material. The surface of a diamond film separated out through CVD is uneven to the extent of 1-2 μm, and the independent substance looks like ground glass. Therefore, it should be polished when necessary.

When used in peepholes, coating the peepholes with diamond-like carbon (DLC), a carbon film resembling diamond, is probably easier to the extent that there are few restrictions on the kind of base material.

(2) Piping

Because there is an increasing requirement for the handling of superhigh-purity chemicals, inner coatings made of diamond, which offers superior corrosion resistance, might be sought. However, pinhole-free coatings in small or long pipes is difficult to achieve at present. Also, SUS, Ti or the like as used as pipe materials. Therefore, prior treatment to crate a situation facilitating diamond separation, such as Ta flame coating, will become necessary.

(3) Containers

Inner coatings of receptacles for superhigh-purity chemicals offer a potential, as in the case of piping, and there are voices calling for the immediate use of diamond coatings for superhigh-purity sulfuric acid containers, if possible.

(4) Cutting Edges

The abrasion of long edges for paper cutting, regarded as a kind of tool and used in the paper manufacturing and printing industries, is posing a problem. Because some of these edges are as long as several meters, one still encounters such problems as pretreatment and undercoating as measures to cope with differences in thermal expansion. As a potential, however, there are expectations for coating such large objects with diamond.

3.2.5.3. Marine Environment

Equipment related to the exploitation of hydrothermal deposits in the oceans probably will have to operate under severe conditions. There is the possibility that diamond will be used to coat the surface of equipment used at high temperatures and pressures at low HP due to the presence of H_2S.

3.2.5.4. Other Purposes

At the first opportunity we want to explore the use of diamond in the context of taking advantage of its affinity for living bodies.

3.2.6. Summary

3.2.6.1. Optical Parts

It is conceivable that diamond can be used for the following optical purposes:

(1) Transmission windows or lenses
(2) Base materials for reflecting mirrors
(3) Protecting film for optical parts

Applications that fall in the first category include transmission windows for X-ray detectors and masks for X-ray lithography, and also window materials for high-energy beams such as high-output lasers. For the former, a high-strength thin film measuring less than 1 μm, free from pinholes or distortion, is necessary. The trial manufacture of this kind of thin film already is underway using gas phase synthesis. The fabrication of a large, uniform thin film is probably a big task for the future. With regard to materials for use in transmission windows for high-energy beams, the high thermal conductivity of diamond together with its other properties, including a low coefficient of thermal expansion and a high modulus of elasticity, are to be fully exploited. In this case, light-absorbing impurities need to be reduced to the minimum. Moreover, this alone does not theoretically bring about a light transmission factor of more than 70 percent, because diamond has a high refraction factor. In the case of the current high-pressure synthesized single crystals, a value close to this theoretical value has been obtained. As for gas phase synthesized diamond, however, the value obtained differs from the theoretical value because of its polycrystalline structure and the presence of nondiamond impurities. The portion other than the 70 percent is the rate of reflection. To reduce this, the technological development of a reflection-preventing multilayer film is necessary if diamond is to be used as a window material.

With regard to the second category, a base material for reflecting mirrors for high-energy beams is conceivable. As in the case of window materials, a high level of thermal conductivity and a small degree of distortion due to heat are among the characteristics of diamond. There are many related tasks, such as the formation of ultrasmooth curve surfaces and designs for radiation structures.

As for the third category, diamond can be used to protect optical parts that are less hard and readily damaged, as in the case of window materials for infrared sensors such as ZnSe. An amorphous carbon film has long been used for

this purpose. Crystalline diamond requires a high temperature for fabrication, and this point needs to be improved in order to use it for current optical materials. Recently, an attempt has been made in the United States to stick a separately fabricated crystalline diamond protecting film to a base material.

3.2.6.2. Thermal Parts

Monocrystalline diamond, which has a high level of thermal conductivity, is currently used for heat sinks for semiconductor lasers, and so forth. Diamond has the potential of being used as an IC substrate material as well. For this purpose, a comparatively thick film with a high level of thermal conductivity needs to be fabricated to cover a large area measuring several inches through gas phase synthesis. It would be ideal if a multilayer film with a wiring layer in between can be fabricated through the development of low-temperature synthesis technology. It also is necessary to evaluate and improve such properties as dielectric constant and dielectric loss.

Recently, it has been reported in the United States that the thermal conductivity of single crystal diamond can be improved markedly by removing the isotopic carbon in diamond. Heat sinks are not formed with diamond itself, and a layer bonded to an element, a radiation environment, and so forth need to be considered. Therefore, one can conclude that the desired effects can be obtained through the concurrent development of utilization technology, instead of improving the thermal conductivity of diamond alone.

3.2.6.3. Audio Parts

An independent, dome-shaped diamond film to be produced through gas phase synthesis has been developed in Japan. This film is designed for use as a speaker diaphragm to reproduce high-frequency sounds. This film is loaded in a comparatively expensive system, but it is expected to become increasingly popular as the manufacturing method is improved. This is an interesting application from a technical point of view as well, in the sense that the film is of a different, independent type. It conceivably will be expanded to different fields as well.

Using diamond for elements with GHz-band elastic surface waves is considered possible through the use of the high acoustic wave transmitting speed of diamond. Research on this application has just begun, and there are many outstanding tasks, including the fabrication of high-quality film by gas phase synthesis, selection of an appropriate piezoelectric thin film material to be formed on a diamond substrate and the technology to form it, and design of an electrode structure.

3.2.6.4. Mechanical Parts

(1) Diamond-Coated Tools

It can be said that this application is closest to realizing the use of gas phase diamond. The tasks to be tackled have been boiled down to a few technical fields including selection of the base material, strengthening of diamond film adhesion, and finish processing. Such tools might be used to cut light or medium loads such as Al alloys, Cu alloys, carbon, FRP, and FRM. For a rapid improvement of adhesion from the standpoint of material science, basic research common with that on the coating of other mechanical members with diamond is felt to be insufficient, and there is a fear that practical use may be delayed because of an over-eagerness for success.

(2) Mechanical Seal

The basic tasks for this kind of seal are the selection of a base material and producing a surface finish with greater precision than is required for cutting tools. It also is necessary to reconsider the selection of a material opposite to diamond. However, the path to application after clearing the barrier to the technical tasks is clear, and, from an engineering point of view, it is an easy target.

(3) Disks and Heads

To further reduce the distance between a magnetic disk and the head to meet the requirement for higher recording density, a protecting film having both abrasion resistance and lubricity is necessary. It is natural for amorphous carbon as well as diamond to be noted as materials for this purpose, given their physical properties.

In this case, too, it is necessary to develop technologies by taking a step backward to address such basic issues as adhesion between the base material and the diamond film, diamond coating technology on a level below 400°C or so where the base material is prevented from changing in quality, and surface smoothness.

In addition, it has been proposed that diamond be used not only for coating but also for plating and for superfinishing bits or abrasion-proof nozzles through brazing a tube to a metal or to an ultrahard alloy. Trial manufacturing for these purposes already is underway.

In any case, the degree of base material selectivity, adhesion to the base material, and finish processing for final manufacture are keys to fulfilling the technical prerequisites for putting gas phase diamond to practical use. Work in none of these areas seems to have passed the stage of testing the various ideas on a trial-and-error basis.

3.2.6.5. Corrosion- and Environment-Proof Parts

(1) Resistance to Chemicals and Abrasion

At normal temperatures, diamond is chemically resistant even to chemicals that are extremely corrosive. At the same time, it is superior in abrasion resistance. For this reason there are devices to transport highly corrosive materials or slurry, windows for reaction equipment, and so forth, that use plate consisting of independent diamond. If metal-based bodies can be coated in complex and elaborate ways, the path will open for the favorable

use of diamond. However, there are as yet few basic techniques for manufacturing adhesive, elaborate diamond-coated films even in the size or form of printing tools, mechanical tools, and so forth. It is thought that still more time will be required to achieve the practical use of parts that are large or have complex forms.

In putting independent plates to practical use, bonding the plates to a frame material will be a very important technical task.

(2) Marine Environment

As a basic material, diamond has the same potentials as those cited above thanks to its chemical stability and its strength. However, in view of the technical conditions in the actual environment, such as the need for larger areas and recoating, there are many engineering tasks that are more difficult.

Thus, in commenting on diamond's resistance to chemicals, its adhesion, and its uses in the marine environment, it is necessary to note that basic technical data on the corrosion resistance and weatherability of diamond, which ultimately will make it possible to arrive at such uses, are utterly insufficient.

(3) Resistance to Radiation and Ultraviolet Rays

It has been noted that diamond has the potential to be used as a semiconductor element suitable for operation in the space environment, in the severe radiation environment of nuclear reactor operations, or even in a high-temperature ultraviolet environment. Diamond also has the potential of becoming a material for renovative element technology where it would be used for such purposes as monitoring the safety of recent nuclear reactors and repairing them. Moreover, the fact that the use of diamond is expected to contribute to the preservation of the global environment and the securing of energy, which is essential for the continued existence of mankind, is extremely significant in the field of diamond applications.

Chapter 4. Conclusion

4.1. What the 21st Century Requires of Industries

It is well known that general reviews of human civilization in the 20th century, and that many attempts to determine what the world will look like in the coming 21st Century have been undertaken, beginning several years before the last decade of the 1900's. In the 1990's, the Soviet Union has undergone a dramatic change, and there have been rapid political and economic reforms in various East European nations, highlighted by the collapse of the Berlin Wall in November 1989 and the subsequent reunification of East and West Germany. Thus, the worldwide political framework that had existed since World War II has collapsed. Moreover, in conjunction with the results of measures to cope with the effects of the Gulf War, which was triggered by the Iraqi invasion of Kuwait in August 1990, there are waves surging toward new international relationships.

It is true that mankind has won unprecedented prosperity in the 20th Century due to the developments in industry, medical treatment, agricultural techniques, and so forth based on the modern science and technology that has emerged since the 19th Century. Some advanced industrial nations are becoming advanced information societies because of the development of electronics.

At the same time, however, we cannot but admit that the bright frontier cultivated by mankind with our modern science and technology with which we will enter the next century also entails a number of consequences that could lead to a "frontier in the dark," so to speak. It is currently being noted in many quarters that the existence of our global environment, which is the stage for mankind, is being menaced by the activities of mankind itself, involving war, poverty, and the explosive increase in population.

We should never approach this situation in a pessimistic way. We should understand, rather, that the future, the 21st Century, is asking those of us living now about the tasks we should tackle in real earnest.

What responses, therefore, should we who are engaged in science and technology or industries make toward the 21st Century? This problem is being studied earnestly in many quarters in many countries, including industrial, academic, and government circles, and various reports have been made in this connection. In July 1990, a report issued by the 1990 Policy Committee of Japan's Industrial Structure Deliberation Council, entitled "Proper Ways of Trade and Industrial Policies for the 1990's," brought together superior reports by intelligent individuals in industrial, academic, and government circles, and these reports have attracted public attention.

In particular, the subtitle of the report, "Creation of Human Values in the Global Age," points in the direction we should follow in the future. In other words, making it possible for "mankind to maintain harmony with the global environment, which is the place for its existence, to live under conditions that are spiritually as well as materially rich, and also to expand the frontier for its existence," is being urged as our essential task.

If mankind does not try to achieve this objective, it will suffer serious consequences, such as damage to the global environment, a widening difference between rich and poor, and stagnation in the arena of human existence and activities due to a huge increase in population. Thus human existence itself could be threatened.

Therefore, it can be said that in the future new industries should be oriented generally in the following three directions:

(1) Harmony between man and nature
(2) Securing of resources and energy
(3) Expansion of the frontier for human activities

To move toward harmony between man and nature, in the first place, industries need to be developed in consonance with the most urgent tasks of today, such as preservation of the global environment, perfection of human life and environments, liberation from the pain of sickness, and enhancement of the medical field with an eye to longevity.

Next, it is believed that securing resources and energy will become an extremely great task as a basis for human existence, including its relationship with the global environment problem.

Calls for limiting the use of oil have been heard many times, but it still has been possible to use oil as the main source of energy thanks to efforts to develop new oil fields and to energy-saving measures. It can be said, however, that today is a full-dress rehearsal and that it is time to tackle earnestly the practical use of energy-saving technology and new energy sources.

Expansion of the frontier for human activities can be regarded as a hopeful, important direction for the industrial field. Mankind, which is expected to number 6.3 billion in the year 2000, should cultivate broader, comfortable fields of activities such as space, the ocean, or deep underground. It goes without saying that this also is based on the principle of maintaining a gentle relationship with nature.

4.2. Allure of Diamond Materials for Future Technologies

4.2.1. Applications of Ultimate Properties Required for Future Industries

Figure 4-1 shows the direction to be followed by the future industries cited in the preceding paragraph, together with materials that conceivably will become principal elements of technologies supporting these industries. This illustration is a summary of the opinions expressed by the members of this committee about materials needing ultimate properties, and diamond in particular.

This illustration makes it clear that there are still many kinds of technologies and products that should be developed. For the development and maturation of an advanced information society, however, more advanced optoelectronic materials, substrates with high radiation ability for superhighly integrated circuits, high electric power control devices, high-performance microwave communication devices, and so forth are being cited as promising fields where diamond can be applied.

In order to deal with problems related to the global environment, the graveness of which increasingly and rapidly is being recognized and highlighted, the properties of diamond can be utilized for high-temperature, lightweight ultraviolet sensors to watch ozone layers, a sandstorm-proof and abrasion-proof material for desert environment observation systems, a high-degree of hydrogen shield material in systems using hydrogen energy, and so forth.

In addition, it is thought that diamond materials that are resistant to various high energy beams can be used for nuclear reactors, which are regarded as an increasingly important energy source, and for space development, which holds an important position in the current trend toward frontier expansion.

Let us next consider the properties of materials by comparing them to the cut ends of a tree. Table 4-1 [table not reproduced] summarizes the properties of principal functional materials that support the current generation of advanced technologies and that will continue to do so in the future. As is well known, such materials feature complete covalent bonding, and therefore display properties that are demonstrably superior to those of other materials. Thanks to their high degree of hardness and high Young's modulus, they can be used not only for familiar tools, but also as materials of the highest rigidity for a wider range of mechanical purposes.

Their thermal conductivity, meanwhile, is five times that of silver at 25°C, for example. Thus they are very attractive primary radiation materials for devices that, in the future, will feature ever-increasing degrees of integration.

From the viewpoint of electronic and electrical properties, it also can be said that diamond and cBN, both of which have a diamond structure, are highly suitable for applications as high band gap materials. The mobility of positive holes and electrons in diamond materials also are fairly high compared to silicon, which currently is used as the base for semiconductor materials. When considered together with such properties as low dielectric constant and high resistance, many interesting composite applications are conceivable.

As for optical properties, the refraction coefficient of diamond materials is extremely high in terms of transparency. The fact that they are transparent for almost all wavelengths from infrared through visible and ultraviolet light also makes them attractive, although this is not mentioned in the table.

Figure 4-1 shows, in the form of a tree, promising products for which diamond is expected to be used in the future, with their properties compared to cut ends. From this illustration, too, it can be easily understood, in light of the aforesaid properties of diamond, that it is possible to develop parts with renovative functions applied so that they can support the advanced technologies in the future.

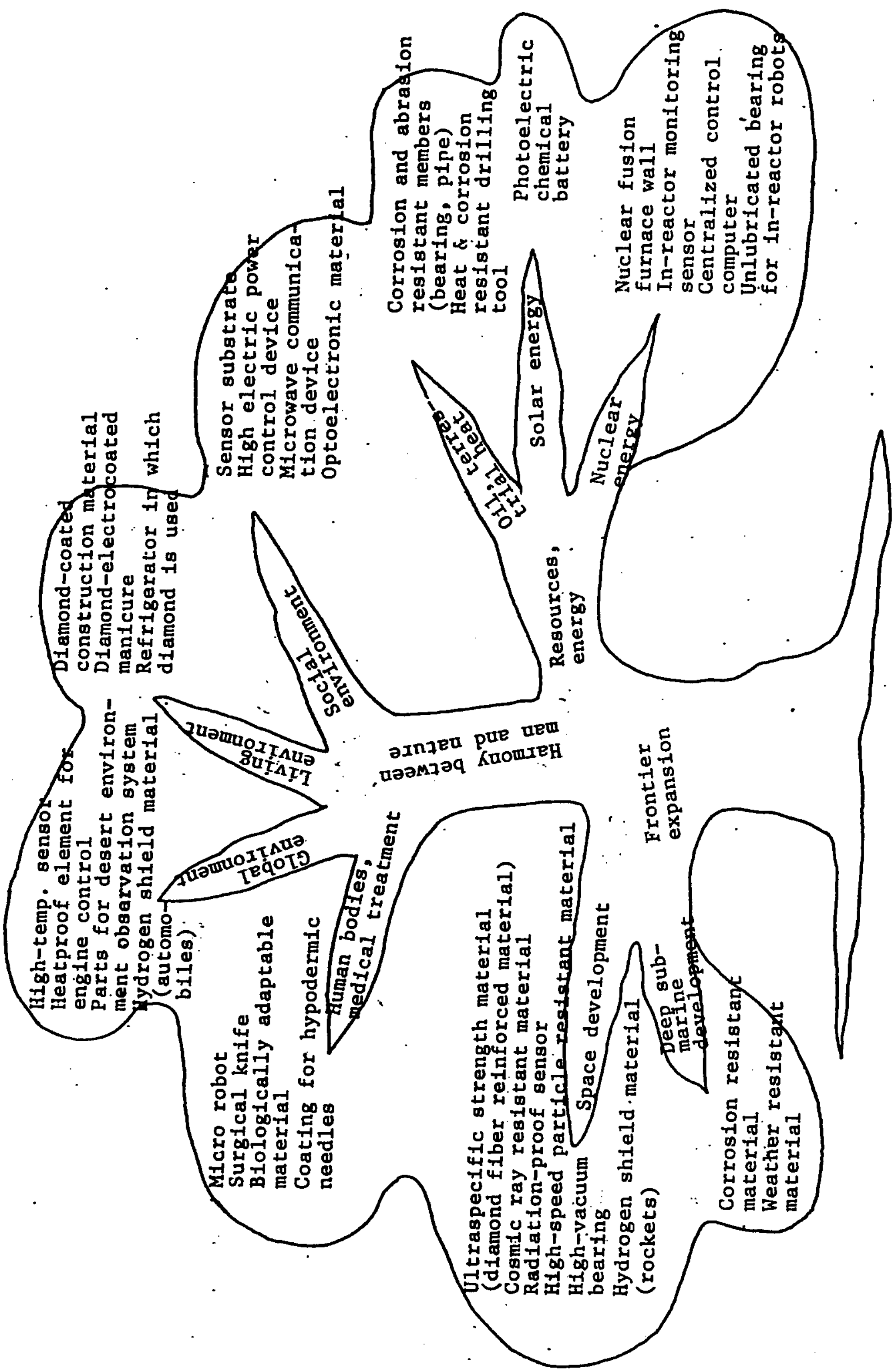

Figure 4-1. Needs for Future Industries and Requisite Technologies To Be Developed: Potential Applications for Diamond

4.2.2. Important Fields of Diamond Applications To Be Developed in the Future, and Tasks

4.2.2.1. Important Fields of Applications Viewed From Social and Technological Needs, and Tasks

Table 4-2 [table not reproduced] summarizes the aforesaid fields that industries should aim at toward the future, technologies supporting these fields, applied parts that are considered important from the standpoint of using diamond.

In other words, the fields that should be aimed at toward the future are roughly group into four parts—the global environment, living and social environments, frontier environments, and resources and energy—and applied parts that are presumed to produce the highest performance through the use of diamond, and technologies and systems finally applying these parts, are listed for these respective items.

This table shows that among the use properties of diamond, its mechanical properties will be noted in the future as well, naturally, in such cases as using it for diamond tools because of its high-degree hardness and rigidity. At the same time, the table shows that its thermal and electronic properties and radiation resistance are also attracting equal or greater attention. It can be said that diamond has potentialities as a highly functional material following silicon, gallium arsenic, and silicon carbide, as already mentioned earlier.

The technological tasks listed in Table 4-2 can be summarized as follows:

(1) Technologies for the manufacture of high-quality diamond.

(2) Technologies for turning diamond into semiconductors and producing devices with them.

(3) Basic manufacturing and processing technologies, including precision processing and bonding.

With regard to high-quality diamond, there are many basic, technological tasks for both polycrystals and monocrystals that need to be resolved. These include ensuring a high degree of purity, doping, and perfection through rigidly controlling reactions at the molecular and atomic levels. Other tasks involve increasing the growth speed and surface area, and securing adhesion to substrate.

As for semiconductor and device technologies, stable homoepitaxial and heteroepitaxial growth, n-type semiconductors, pn junctions, electrode formation, and so forth are currently under study. These studies have just begun, however, and it safely can be said that few studies actually are being conducted. Thus, no guidance has been established yet.

Basic technologies, however, including precision processing and junctions, can be taken up as technological tasks at the final stage of putting diamond materials to practical use. Diamond, which to date has been used on the processing side, has now moved to the side of being processed. Moreover, it has the highest degree of hardness among materials. Therefore, a drastic new concept is desired. In addition, the problem of bonding to other materials is an extremely big task for the practical assembly process.

With regard to these various technological tasks, the relative difficulty of technologies was evaluated by this committee, and the results are shown in Table 4-3 [table not reproduced]. In conducting the evaluation, the following four levels were established:

A: It is necessary to start by accumulating basic, scientific knowledge.

B: Basic scientific knowledge exists, but drastic ways of thinking are necessary to create technologies.

C: There are many ideas, but extensive, systematic studies are necessary to establish technologies.

D: The competitive base of enterprises is sufficient.

In evaluating the relative difficulty referred to in the table, most of the cases fall under levels B and C pertaining to basic technologies, and in some cases they fall under level A. There are fairly grave risks involved in tackling these tasks on an enterprise level, and also there are many cases in which schedules are hard to read. However, it can be said that the evaluation is being focused on those tasks relative to basic engineering that will have great technological impacts in case of success.

4.2.2.2. Future Market for Diamond-Used Products

In light of the technologies and physical properties that will be sought in the future, applications and the development of diamond should prove to be extremely colorful, as described above. Ultimately, however, whether the market is large or small will be important for industry.

Currently, the market for diamond products is still at the stage of development or groping research. The exception is diamond tools, which already have been established. This to some extent is a presumption based on a survey conducted some time ago by the New Diamond Forum with its members as respondents.

The annual output of diamond tools, including cBN, exceeded ¥100 billion in 1990. In the year 2000 output is expected to amount of ¥260 billion, while that of abrasion-proof and sliding products incorporating gas phase diamond applied presumably will amount of ¥320 billion. Of this, ¥280 billion represents the output of optical and magnetic heads and disks. However, it is necessary to restudy whether or not these can actually be achieved in such a time span.

It also is estimated that diamond heat sink production will amount to ¥50 billion, semiconductor production to ¥25 billion, and optical applications to ¥50 billion,

totaling ¥125 billion. The extensive utilization of diamond properties has been at the stage of research and development over the past 10 years or so, and it is still fairly difficult to put diamond materials to practical use. In addition, although the manufactured products are highly functional, there are limits to the extent of their use and to the manufacturing cost. From these points of view, the forecasts are conservative. Since 1989 when the survey was carried out, further case studies have been made on product design and manufacturing cost on the basis of accumulated technological information. It is necessary to look again at the future market for diamond products in comparison with other competitive materials.

Within the limits of the information currently obtainable, annual production for the year 2000 is estimated at ¥260 billion for tools, ¥320 billion for abrasion-proof and sliding products, and ¥125 billion for highly functional products including semiconductors, and thermal and optical products, a total of about ¥700 billion. However, with regard to the necessity for restudy, and with the subsequent research and development in mind, as well as the period required for the restudy, we think that themes at the level of national projects should be considered to require a total time span of about 20 years, estimating the period for development at about 10 years, and that industrialization will take place 10 years after that.

4.3. Approach to Fulfilling Technological Tasks

Returning to Table 4-3 [table not reproduced] we believe that the tasks included in category D in terms of their relative difficulty can be accomplished through competition among enterprises. When technological tasks involve many difficulties, such as those in category A, we believe an appropriate approach would be for universities to take the lead, focusing on explanations in terms of basic science.

The tasks ranked in categories B and C in terms of relative difficulty conceivably can be tackled in the form of projects with various sectors and countries cooperating with one another, in view of the investments in development, the time required, and the degree of risk involved in these enterprises.

When the ultimate properties of diamond are considered, it must be said that developing highly functional products and contributing to the intellectual assets commonly owned by mankind are extremely important in the sense of providing technologies for solving global problems that affect all mankind, such as preserving the global environment, perfecting the living and social environments, expanding the frontier, and securing resources and energy.

The themes for joint projects have been described already, but we will list them again as follows, having revised the way in which they are expressed:

(1) Technology for manufacturing high-quality diamond through process control at the atomic and molecular levels.

(2) Technology for using diamond to produce semiconductors and devices.

(3) Technology for the precision processing of diamond.

(4) Technology for bonding diamond to other materials.

This committee thinks that the following basic viewpoints are essential if these themes are to be tackled jointly:

(1) Making Projects Global

It is necessary to overcome the international friction that exists in advanced science and technology by making people more aware of the need to form intellectual assets that are the property of all mankind from a still broader global viewpoint. This would mark a step beyond the current level of cooperation among nations.

(2) Opening Japan to the World as a Base for Exporting New Basic Technologies

It is necessary for Japan to increase the participation of various Western countries in national projects, for example, and to set up concrete systems such as an international advisory and evaluation committee.

(3) Opening Intellectual Ownership of Development Results

Basic technologies should be made available to participating members on the principle that they are to be owned jointly. On this basis, concrete, downstream applications should flourish and multiply with increasing speed. With regard to ownership and other issues related to the use of basic technologies and final manufactured products, ownership should be structured so as to reward inventors' contributions fully. On this point, however, we anticipate that international coordination will be very difficult, and therefore it may be necessary for Japan to begin by making a concrete decision to "give."

4.4 Issues for Future Study

Keeping in mind the significance of realizing a diamond industry and ways to approach the problem, we think that the following issues should be studied in the next fiscal year in order to achieve concrete projects:

(1) Concrete proposals for development tasks and clarification of a level to fulfill them.

These could be achieved, for example, by estimating the target performance of products using heat or semiconductors, and a system to manufacture them, or by undertaking case studies of trial cost calculations.

(2) Market forecasts.

(3) Proposals for promotion systems.

Domestic systems
Global mechanisms

(4) Clarification of basic ways of thinking about the use of results.

(5) Schedules and budgetary appropriations.

To make the global start smooth, we think it desirable to have committee members from abroad participate in some form from the stage of investigation and research beginning in the next fiscal year.

Chapter 5. Proposal

Basic Technologies for Diamond and Ultimate Functional Materials Should Be Established

Today, the end of the 20th century, which often seems like it is still far away, is just around the corner. At this juncture, mankind is faced with a number of global problems of unprecedented seriousness. These problems include the worldwide reform of the political order, the damage to the global environment, the rapid increase in population, and the drain of resources and energy. In response to the inevitable questions to be asked from the 21st century about these problems, we must endeavor, with all available wisdom, to create an environment in which all mankind can live affluently, enjoying both the material and spiritual aspects of this beautiful earth.

We, who are concerned with science and technology as well as industries, in such a situation recognize that three points—(1) harmony between man and nature, (2) securing resources and energy, and (3) expanding the frontier of human activities—are the most important directions for industries to follow in the future.

We gave a more concrete expression to these tasks as follows: (1) ensuring comfortable global environments, (2) perfecting living and social environments, and (3) expanding the frontier. We then repeated studies of technologies that could be used to attain these targets. As a result, we have become strongly convinced that we are being pressed to develop innovative technologies even beyond the level we have currently reached.

There are numerous technologies and manufactured products in need of great leaps forward. These include a lightweight, heatproof ultraviolet sensor for the continuous monitoring of the state of the ozone layer, high-output elements and substrates for high electric power control systems, high-performance elastic surface wave elements for satellites and moving communications equipment, radiation resistant sensors for in-reactor monitoring systems, infrared parts for space observation systems, materials that are resistant to cosmic rays, and high-vacuum low-friction materials.

Recognizing that improving highly functional key materials already existent, such as silicon and gallium arsenic, and also that developing even more advanced functional materials is essential for the success of such technological reform, this committee took notice of diamond, which already was known to have many ultimate properties, and compared the basic properties of diamond with those of the aforesaid existing high-performance materials. As a result of exploring feasible applications of these materials, it has become clear that diamond has the potential to become an extremely superior key industrial material.

In examining the potential applications of diamond, however, we cannot but recognize that little basic scientific and technological research has been carried out, and that such research has only just begun.

Therefore, this committee proposes that the following major tasks be tackled as research and development projects from a global point of view in order to build a basis on which to make diamond a highly functional material, to realize renovative technologies to settle global problems, and to form a foundation to develop a new diamond industry:

(1) Technologies for manufacturing high-quality diamond through process control at the atomic and molecular levels.

(2) Technologies for using diamond to produce semiconductors and devices.

(3) Technologies for the precision processing of diamond.

(4) Technologies for bond diamonding to other materials.

In particular, we strongly urge that a decisive international framework be created, one that will take advantage of the strong points of already completed projects, so that our country will become a point for the dissemination of basic science and technology, thereby making this a means for contributing to the earth and to all mankind.

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